A 500 V Fast Switch For ProjectX 200 Ohm Chopper

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ABSTRACT

The ProjectX chopper (kicker) will deflect part of the 162.5 MHz beam towards an absorber. The 200 Ohm traveling wave electrostatic kicker design approach allows lowing power dissipation in the driver, kicker and load by the factor of 4, compared to a 50 Ohm structure. The chopper is made from two 200 Ohm helical microstrip lines that are facing each other. This structure should be driven by at least 500 V pulses. Due to the 6.15 ns spacing between the centers of bunches, leading and falling edge rise times of driver pulses should be not more than 2 ns. The length of pulses should be adjustable from 3 ns to units of microseconds. This paper describes the prototype of a switch intended to meet described specifications.

INTRODUCTION

The chopper used in ProjectX MEBT (Medium Energy Beam Transport) is used to deviate part of the 162.5 MHz beam towards an absorber. The idea of using 200 Ohm impedance allows decreasing power dissipation in the driver, kicker and the load. The chopper is made from two 200 Ohm helical microstrip lines that are facing each other. These are half meter long kickers. Due to the specifications the beam chopper should be driven with 500 V pulses. The frequency of the beam is 162.5 MHz, so the distance between two adjacent bunches is 6.15 ns. This is the reason the rising/falling time of the driving signal should be less or equal 2 ns. To be able to provide beam for different Project X experiments, the chopper should kick bunches in the wide range of timing – from 3 ns to microseconds. Also wide repetition rate is required – up to 30 MHz. The specific timing will vary depending on beam required by the experiments, but the requirements are that the switch be high speed, high repetition rate and high duty factor.

PROBLEM REVIEW

Unfortunately, there are no individual semiconductors available on the market that can absolutely satisfy described specifications. Known IGBTs or bipolar transistors are not fast enough. Fast high voltage MOSFETs used in [1] have low maximum voltage. The fastest 1 kV MOSFETs available are rated 5 ns minimum rise time and very high output capacitance (more than 100 pF). This capacitance results in too much switching losses at high repetition rates.

Vacuum tubes are fast enough and can provide high power and voltages. For example, the 3CPX8007 vacuum triode can handle on up to 4.5 kV voltage and has a broadband of 500 MHz that allows it to produce less than 2 ns rise times. Unfortunately, low maximum plate current of tubes does not allow using only one tube to drive 200 Ohm load at 500 V. And in that case there is a necessity to connect several tubes in parallel to make a distributed amplifier. However, due to the estimates that were made, bandwidth of such amplifier will be low. Also, directly connecting tubes in parallel would increase rise time too much due to the combined output capacitance.

Another way to produce required fast impulses suitable for 200 Ohm load is to make a coaxial transmission line power combiner from four 50 Ohm cables. These combiners can have, for example, four 50 Ohm, 150 V grounded fast generators, which are driving four broadband 50 Ohm ferrite “transformers” that are wired as common mode chokes. The 50 Ohm outputs of these “transformers” would be connected in series. The output of such combiner voltage and impedance of each primary generator is multiplied by factor of 4 and even 600 V and less than 1 ns rise/fall time pulses could be delivered to the 200 Ohm load. Capacitive coupling the transformer inputs allows the combiner to be used at even high duty factors. One problem, though, is that the signal is AC coupled.

All these facts lead to a conclusion that now one possible way of achieving fast and powerful impulses is to make a transistor *switch*. Due to the absence of suitable high voltage low capacitance transistors the only way to achieve high speeds at high voltages and repetition rates is connecting relatively low voltage (100-150V), low output capacitance fast transistors in series.

SWITCH DESIGN

The basic idea of how a 500 V transistor switch can drive the 200 Ohm kicker is shown on figure 1. It shows a push-pull driver and a kicker that is biased to the common mode +250 V voltage. This allows to minimize power dissipation in 200 Ohm load by factor of four compared to simply grounding the load.

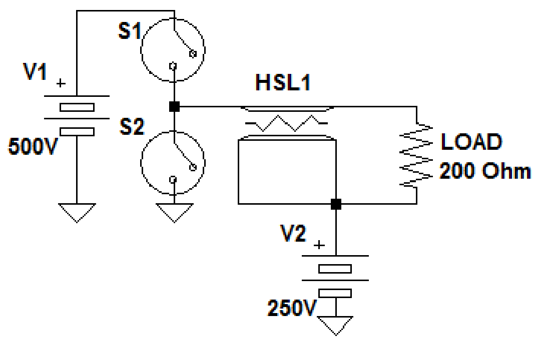

Fig.1 – Unipolar 1/2 kicker

Minimum power is achieved by the fact that when S1 is closed there is 500 V delivered to the kicker and only 250 V across 200 Ohm resistor, compared to the situation if the load is grounded. Voltage across the load is 250 V; voltage is reduced by two and load power is reduced by factor of four.

Figure 2 shows how four switches drive the full kicker.

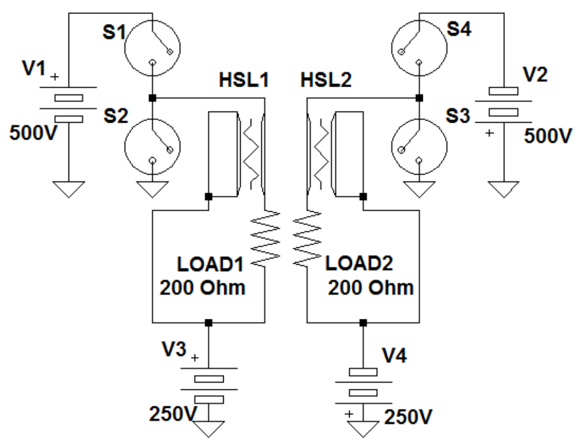

Fig. 2 – Unipolar kicker driver

The circuit of figure 2 shows two helical microstrip lines HSL1 and HSL2. The push-pull drivers work the same way as circuit in fig.1. The significant difference of this circuit is that battery V2 is negative 500 V out. This means that when S1 and S4 are closed the potential between microstrip lines HSL1 and HSL2 (that are facing each other) is 1000 V. This electric field kicks out the beam.

The significant question is the design of the S1-S4 switches. It has been already concluded, that one of the ways to create such switches is to connect low voltage fast transistors in series.

A cascode switch topology provides a way for transistors connected in series to share voltage. The simplified circuit diagram is shown on figure 3. The circuit of figure 3 consists of four GaN transistors J1-J4, made by Polyfet RF Devices. Breakdown drain-to-source voltage is 200 V. Maximum CW current is about 5 A. Experiments show that it is possible to achieve 600 ps rise times with them. GaN transistors are depletion mode parts and need negative voltage on the gate to turn them off. There are also sub circuits PC1-PC3 that are protection circuits and work as voltage clamps. They are described later in the paper.

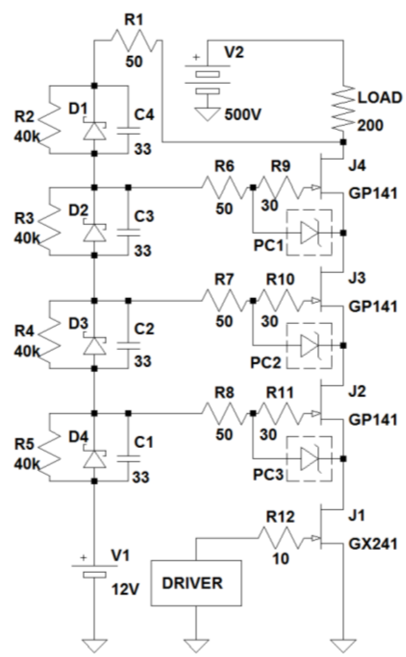

Fig. 3 – Simplified cascode switch circuit

The circuit of figure 3 works as follows: assume that J1 is open and an off-signal is coming from Driver to J1. Capacitors C1-C4 and resistors R5-R2 are an AC matched voltage divider. Equal voltage is across capacitors C1, C2, C3 and C4. Sub circuits PC1-PC3 provide negative voltage for the gates of J4-J2, so transistors are completely opened. Now, assume that the driver provides an on-signal for the gate of J1 and it starts to turn on. Drain-to-source resistance of J1 decreases. Current from C1 starts to run to ground through the drain of J1, and J2 gate-to-source capacitance charges to positive voltage. J2 starts to turn on. Current from C2 starts to charge J3 gate capacitance and so on. In fact all four transistors start to turn on at the same time together with J1. While resistance of the transistor string goes down, current through the 200 Ohm load goes up and voltage appears across 200 Ohm load. When the driver turns off J1 the current stops flowing through the FETs. This causes the C1-C4 capacitor string to charge through R1. All FETs will again be off.

Concerning other elements in the circuit: resistor R1 defines charge time needed to charge capacitor string in the divider. This RC time constant should be much smaller than the minimum delay between switch cycles – roughly 8 ns, otherwise capacitors will not charge to full voltage.

Diodes D1-D4 work together with battery V1. Because of the parasitic inductances between transistors ringing occurs at the FET drains while switching. These parasitic oscillations cause the drains to go to negative potential. It would cause negative voltages on capacitors C1-C4 and cause the gates to loose drive voltage. Battery V1 keeps the voltage in the bottom of the string to stay well above ground, and diodes D1-D4 prevent voltage across C1-C4 from going negative.

The design of gate protection circuits (voltage clamps) PC1-PC3 is shown on figure 4.

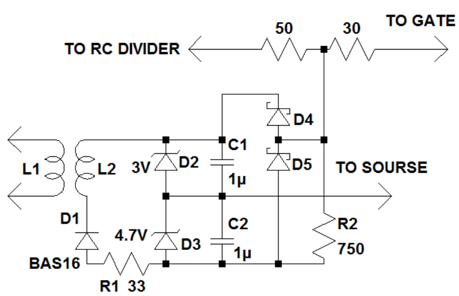

Fig. 4 – Voltage clamp circuit

In figure 4 L1 and L2 are windings of a ferrite transformer. L1 has 1 turn and L2 has 6 turns. There is a voltage clamp for each of the common gate stages. Primary windings of them are connected in series and receive power from a 1 MHz AC power generator.

Circuit works as follows: D1 rectifies current from L2. This current charges capacitor divider C1/C2. Voltage across C1 and C2 is defined by Zener diodes D2 and D3. Their values define the highest and the lowest maximum voltages that can be applied to the gate of transistor, which are +3 V and -4.7 V, respectively. Assume voltage that comes from RC divider is more than +3V on a gate relative to the source. The gate voltage is clamped to the voltage across D2 when diode D4 turns on. This is similar when gate voltage received from RC divider will try to drive the gate less than -4.7 V. In this case D5 will turn on and gate to source voltage is clamped to the negative voltage across D3. Resistor R2 is needed to provide -4.7 V for the gate to keep it off when the driver turns the cascode FET string off.

DRIVER DESIGN

It is necessary that the rise/fall time of the drive stage be less than 1 ns. The basic idea of this driver is shown on figure 5. It can provide pulse width as narrow as 3 ns (full width and half max) and rise times less than 1 ns.

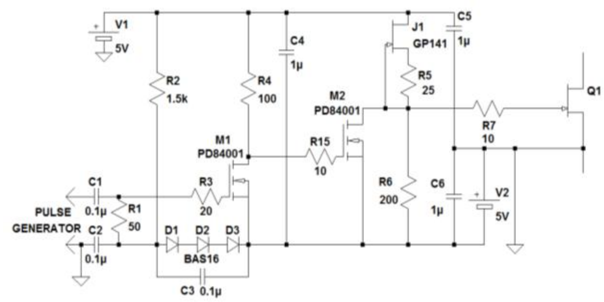

Fig. 5 – Drive stage circuit

In figure 5 transistor Q1 is the first transistor in the cascode switch (see figure 3). The driver works as follows. Assume there is no signal from the pulse generator. In this case M1 is open, M2 is closed. The gate of Q1 is connected to -5 V (see fig. 3). Q1 is open. Now, assume that +2.7 V (which will be the drive signal level in the future) comes from pulse generator to the gate of M1. From the datasheet for PD84001 it can be seen that 2.7 V is not enough for it to turn on. That is why diodes D1-D3 are used. Together with resistor R2 and capacitor C3 they work like an additional power supply and keep the gate of M1 always above +1.8 V. That is not enough for transistor to turn on, but when +2.7 V comes from pulse generator there will be +4.5 V on the gate and it is enough for M1 to turn fully on. So when M1 closes, M2 opens and current runs from the source of Q1 through C5, J1 and R5 to the gate of Q1 until gate capacitance will be charged to +5 V. When that happens Q1 is fully turned on. J1 with R5 act as a current source that charges gate capacitance faster than with a resistor alone. When M1 turns off, M2 closes and current now runs from gate of Q1 through M2 and C6 to the source of Q1 until gate capacitance will be charged to -5 V. When that happens, Q1 will be fully off.

RESULTS

A current switch was made with five transistors, and 480 V pulses to a 200 Ohm load were achieved. The basic construction of the switch can be seen on fig. 6.

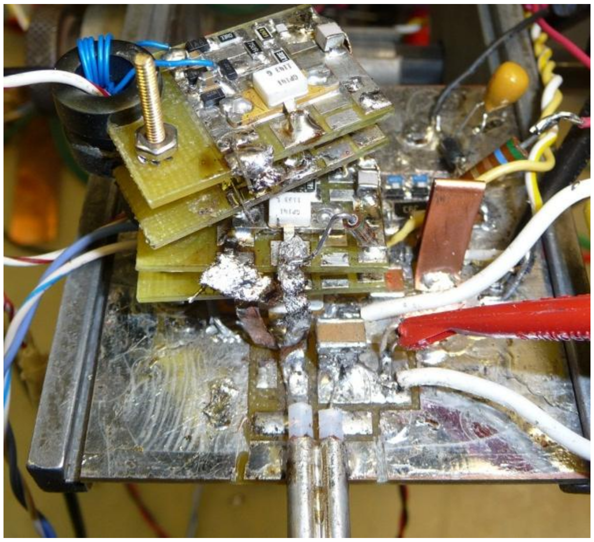

Fig. 6 – Cascode switch construction

Boards with transistors are arranged one above other. There can be also seen 1 MHz ferrite transformers that provide power for the gate circuit of each stage.

The cascode switch circuit is still in development and allows working only with low duty factors and frequencies. The drain voltages of the board in figure 6 can be seen in figure 7.

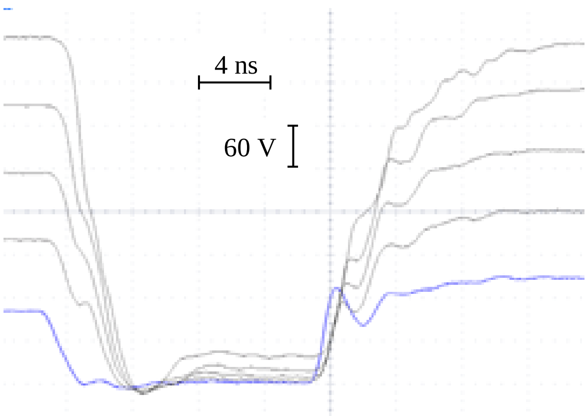

Fig. 7 – Drain voltages of all FETs

These oscillograms were taken from the circuit that is similar to fig. 3 but has 5 transistors. It can be seen that trailing edge is more than 2 ns, but this should not cause problems. In the final push-pull circuit there will be a second switch, as shown in fig. 1 that will discharge switch capacitance to ground, and the falling edge will not be so slow.

Also, it is necessary to say some words about parasitic ringing in the pulse which can be observed on fig. 7. Simulations in LTSpice show that the main reason for that are parasitic inductances in connections between stages, especially in the connection from the Q1 drain. One of the ways to damp such oscillations is to use parallel connected inductor and resistor as the connections between stages with transistors. This circuit works as follows. At low frequencies impedance of inductor is low and all current runs through it. While at the higher frequency of the ringing current goes through the resistor and parasitic oscillations are damped by the resistor. Calculations show, that this resistor should be more than 100 Ohm.

CONCLUSIONS

During work new ideas of cascode switch were described. GaN transistors were tested, and it is shown that it is possible to achieve low rising times with them. The driver for these transistors was designed. First experiments with cascode switch on GaN transistors were made. Fast pulses with amplitude of 480 V on a 200 Ohm load were achieved.

REFERENCES

1. M. M. Paoluzzi “A Fast 650V Chopper Driver”, Proccedings of IPAC2011, San Sebastian, Spain, 2011