SLAC-R-1059

Conceptual Design for CLIC Gun Pulser

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*This material is based upon work supported by the U.S. Department of Energy, Office of Science,
Office of Basic Energy Sciences, under Contract No. DE-AC02-76SF00515 and WFO.*

Introduction

The Compact Linear Collider (CLIC) is a proposed future electron-positron collider, designed to perform collisions at energies from 0.5 to 5 TeV, with a nominal design optimized for 3 TeV (Dannheim, 2012). The Drive Beam Accelerator consists of a thermionic DC gun, bunching section and an accelerating section. The thermionic gun needs deliver a long (~143us) pulse of current into the buncher. A pulser is needed to drive grid of the gun to generate a stable current output. This report explores the requirements of the gun pulser and potential solutions to regulate grid current.

Pulser Parameters and Analysis

The CLIC gun needs to generate a 143us long current pulse to feed the accelerator. A review of the CLIC gun design was performed by SLAC [1]. In this follow-on report, the key parameters of the grid pulser were derived from the review report. These parameters will be summarized and discussed.

Pulse Width, Repetition rate and Floating Deck Voltage

Some parameters of the pulser are directly related to the CLIC Thermionic Gun Requirements. Therefore, Table 1 is cited below from the gun design report [1]. Parameters passed directly to the pulser are highlighted.

Table 1. CLIC Thermionic Gun Requirements

Parameter	Nominal value	Unit
Beam Energy	100-150 (140 nominal)	keV
Pulse Length	140.3	µs
Beam current	5 – 6.6	A
Bunch spacing/Freq.	2/500	ns, MHz
Emittance, N, edge	<25	π-mm-mrad
Repetition rate	50	Hz
Beam radius at gun exit	< 10	mm
Vacuum	10^{-9}	mbar

The pulse width and pulse repetition rate are directly linked to those parameters of the gun. According to the requirements, the pulser need to deliver 140.3 us long pulse into grid of the gun and be able to operate at a repetition rate of 50Hz. Duty can be derived from these two numbers, which is about 0.7%.

The beam energy of the gun determines the HV required for the floating deck. In a typical gun driver system, the cathode, grid and filament are all float at negative potential specified by beam energy while the anode is the ground reference. Therefore, a negative 140kV nominal voltage is required for the HV power supply.

A visual reorientation of the pulse structure is shown in Figure 1. Pulser output current has the same timing requirements but different amplitude compared with those for the gun output pulse. Rise and fall time of the beam current is not critical in this application, so they can be relaxed to ~0.5us.

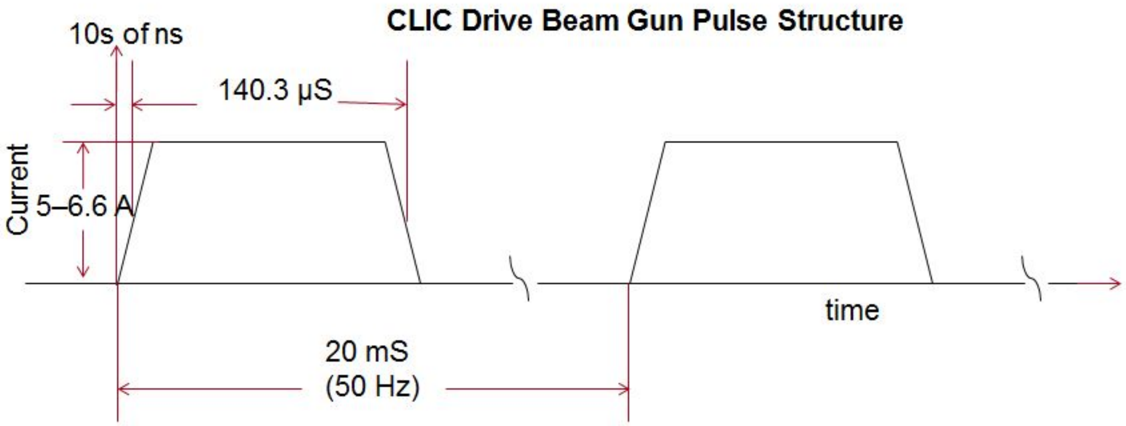

Figure 1. CLIC Drive Beam Gun Pulse Structure

Voltage, Peak Current and Average Current

The grid pulser connected between the cathode and the grid. The grid is on high potential when current is delivered. Depending on reference point, the pulser ouput voltage may be negative (grid referenced) or positive (cathode referenced).

There are two currents in a gun system, which are grid interception current and beam/delivered current. As shown in Figure 2, configurations of the floating deck HV reference point determine how pulser current is calculated from grid interception current and delivered current.

Configuration (b) in Figure 2 has the advantage of lower pulser current. One potential problem of this configuration is that HVPS needs to supply current to the cathode. In this configuration, the parasitic inductance seen by the cathode and grid is much larger, which may cause ringing and/or oscillation. As a result, configuration (a) is most widely used in gun pulser system. Therefore, configuration (a) is assumed in this report.

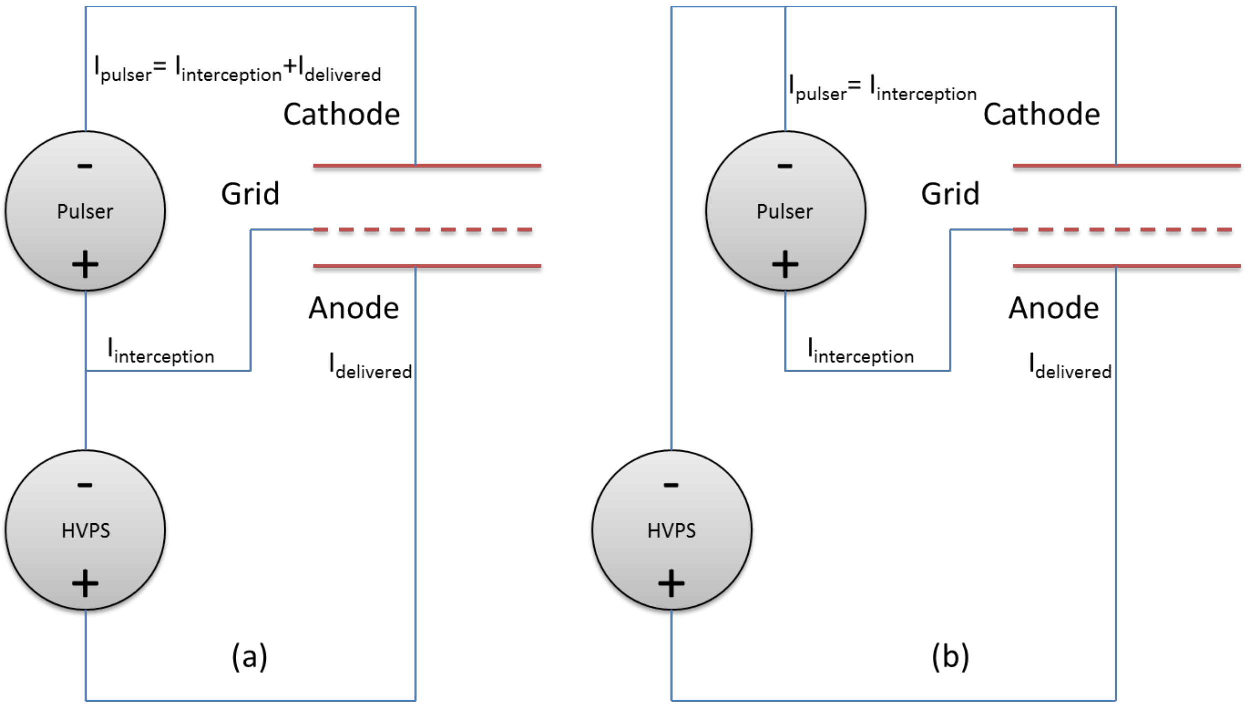

Figure 2. Pulser current and floating deck configuration

Grid interception current and delivered current are investigated in the gun design report. Figure 8 in the report [1] is cited below.

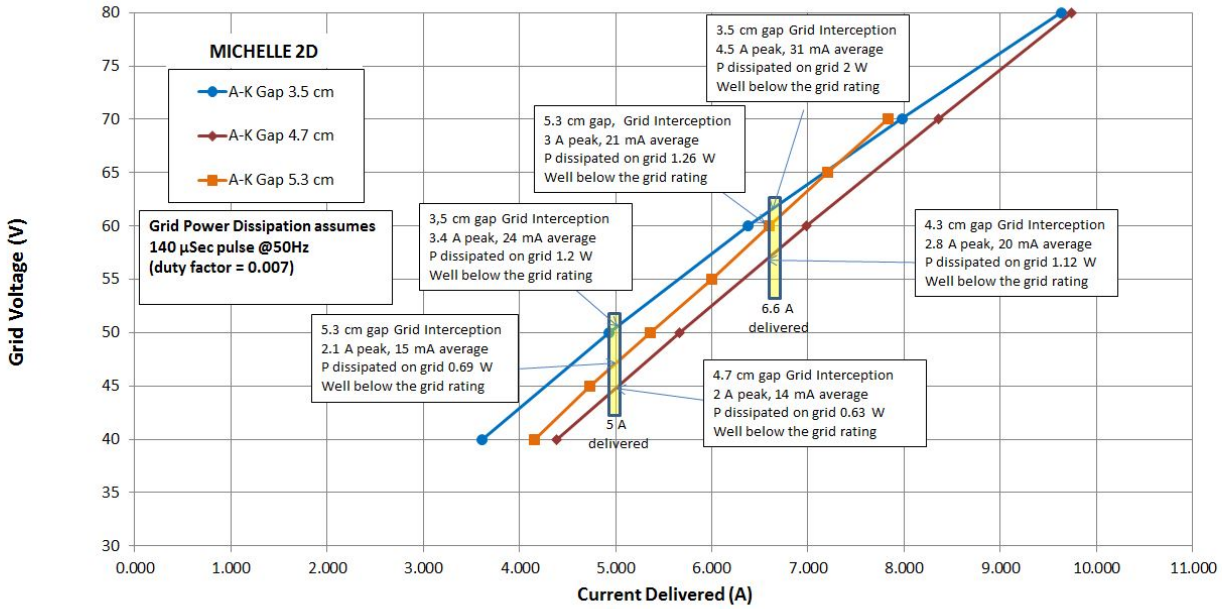

Figure 3. MICHELLE 3D with Grid simulation of grid voltage vs current delivered for 3 cases

Grid interception current, delivered current as well as grid voltage are extracted from Figure 3 and complied into Table 2. Total grid current and impedance seen by grid pulser are also calculated.

Table 2. Grid-Anode voltage, grid interception current and impedance seen by pulser

A-K Gap (cm)	3.5	4.7	5.3
Delivered current (A)	5		
Grid current (A)	3.4	2.0	2.1
Pulser Current (A)	8.4	7.0	7.1
Grid Voltage (V)	50	45	47
Impedance (Ohm)	6.0	6.4	6.6
Delivered current (A)	6.6		
Grid current (A)	4.5	2.8	3.0
Pulser Current (A)	11.1	9.4	9.6
Grid Voltage (V)	62	57	60
Impedance (Ohm)	5.6	6.1	6.3

The worst case voltage and current from Table 2 is 62V and 11.1A respectively. A 50% safety margin brings the numbers to 93V and 16.7A. Rounding up those two numbers gives 100V and 20A, which are used for pulser design.

Droop and stability

In most cases, variation of the flattop part of a delivered current is required to be less than 0.1%. Pulser current is proportional to delivered current so it shares the same 0.1% stability requirement.

Grid voltage and pulser current is controlled by the perveance law illustrated below.

$$I = P \cdot V^{\frac{3}{2}}$$

Variation of voltage in terms of current can be derived.

$$\frac{dV}{V} = \frac{2}{3} \cdot \frac{dI}{I}$$

Therefore, the voltage stability should be 0.067% in order to have a 0.1% stability in delivered current.

Summary of Pulser parameters

Table 3 summarized all parameters used in this report for grid pulser design. The pulse length is rounded up to 150us which gives about a 7% margin. As discussed in previous section, a>50% margin is adopted for output voltage and current.

Table 3. Pulser Parameters

Parameter	Nominal value	Unit
Cathode-Anode voltage	100-150 (140 nominal)	kV
Pulse Length	150	µs
Output voltage (max)	100	V
Output current (max)	20	A
Load impedance	5	Ohm
Repetition rate	50	Hz
Flattop voltage variation	<0.067	%
Current variation	<0.1	%

SLAC CID gun pulser

The electron gun design proposed in the report [1] is similar to CID gun in SLAC [2]. SLAC CID gun pulser can deliver up to 300V pulse into a 50 Ohm load for a maximum length of 5us. Compared with CLIC pulser requirements, one of the major differences is the maximum pulse width, which is about 30 times larger than CID pulser. This difference may cause a big challenge for the gun pulser due to droop from extended pulse length. Another important difference is output current, which is ~6A for CID pulser and 20A for CLIC pulser. A higher output current leads to a larger droop on the storage capacitor therefore worsens pulser flattop regulation.

As shown in Figure 4, the long pulse system of the CID gun includes a high voltage N-type MOSFET Q7 (VN0340N5), and storage capacitors (C28 and C27). When Q7 is triggered, it will connect the storage capacitor to pulser output and generate HV output. At maximum pulse width, voltage on capacitors will drop (300V/50Ohm*5us/20uF=1.5V or 0.5%).

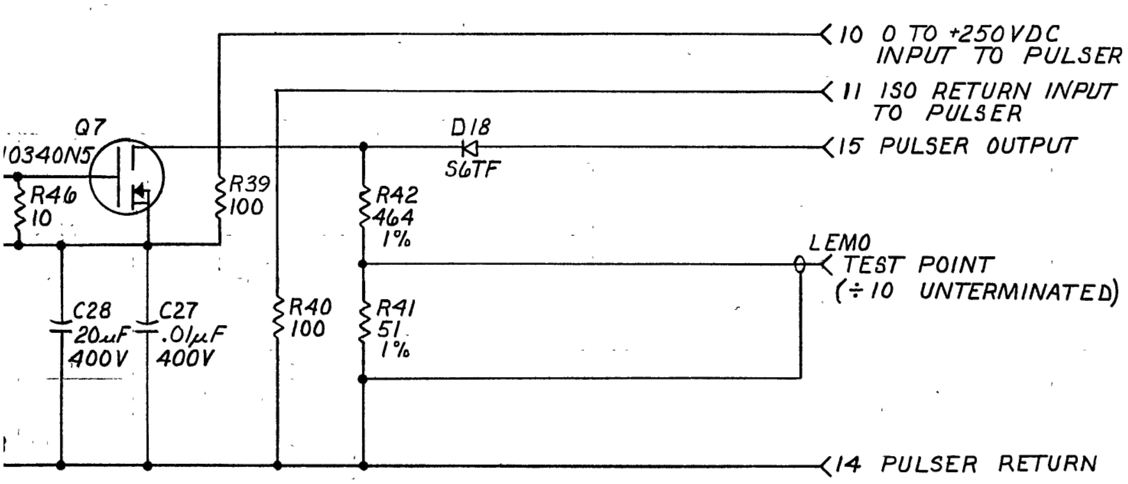

Figure 4. Long pulse system for CID gun pulser [3]

Pulser system diagram

A simplified gun pulser system is shown in Figure 5. The pulser is located in a floating deck which is connected to a negative HV power supply. The HV output of the power supply defines the beam energy of the gun.

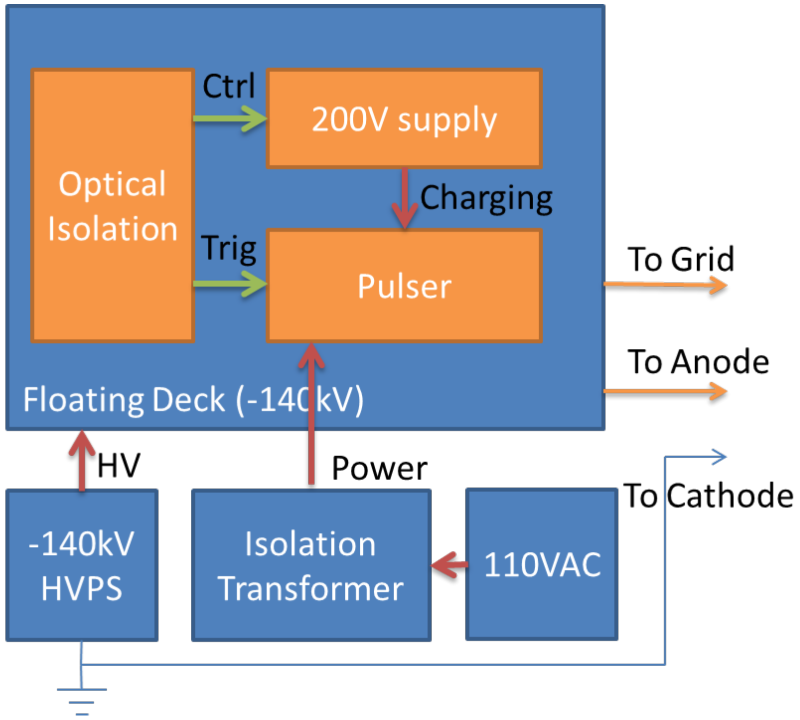

Figure 5. Simplified gun pulser diagram

Proposed solution

As discussed in the previous sections, the biggest challenge of the pulser for CLIC gun is to deliver a low droop stable long pulse. The rise and fall time of 0.5us can be easily achieved by a modern semiconductor switch such as MOSFET or IGBT. Blocking voltage rating can be as high as 1.5kV for MOFET and 6.5kV for IGBT. Pulse current of 20A is also reasonable rating for solid state switches. Paralleling multiple switches is possible to widen selections of solid state switches. A low duty cycle (0.7%) of the pulser ensures that the switch will not run into thermal limitation.

Generally speaking, there are two options to reduce droop related to long pulse at high current, passive regulation and active regulation. Pros and cons of both methods are listed in Table 4. Detailed analysis of both methods will be discussed in next two sections.

Table 4. Comparison of passive and active regulation

	Passive regulation	Active regulation
Implementation	Large capacitor bank for energy storage	Solid state device as variable resistor
Pros	• Simple circuit • Low risk • Well defined result	• Small stored energy • Smaller size • Regulate output current
Cons	• Large stored energy • Large size • Regulate output voltage	• Complicated circuit • Require high bandwidth feedback • Ripple/ring on output

Passive regulation: pulser with large capacitor bank

One solution to reduce drooping for a long pulse is to use a large capacitor bank. By increasing capacitance of the main storage capacitor, less voltage change is expected. A reasonable storage capacitance needs to be determined since a larger capacitor may not be practical and it stores more energy which may cause electric hazard.

As shown in Figure 6, minimum storage capacitances for different output current droop are plotted at different output condition. In the worst case (100V, 20A), 45mF is needed in order to have better than 0.1% droop. Capacitance decrease rapidly when higher droop is accepted. For a 0.5% droop (similar to SLAC CID gun), 9mF is needed for 20A pulser current. In nominal operation, the pulser output current is close to 10A which will reduce storage capacitance to 22.5mF and 4.5mF respectively for 0.1% and 0.5% droop.

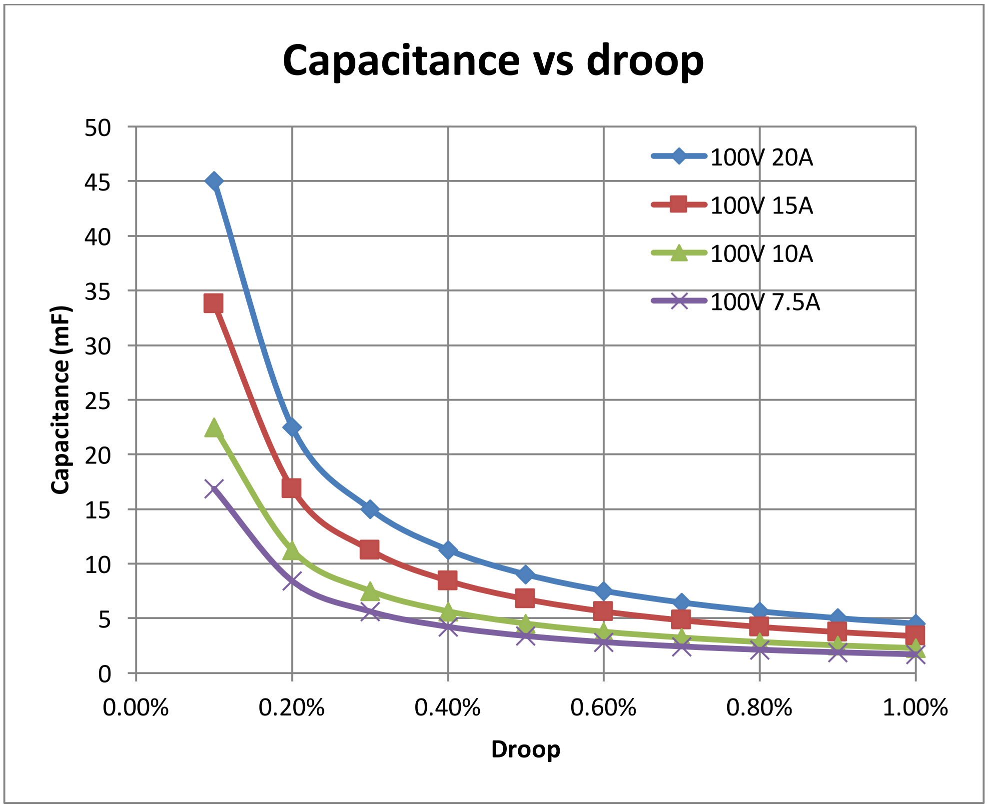

Figure 6. Minimum capacitance for different output current droop, 150us long pulse

It is possible to build a 10s mF capacitor bank operated at 100V. As shown in Table 5, there are mF range capacitors available to build capacitor bank. It is possible to put a capacitor bank of a few mF on the pulser board. If tens of mF is needed, a separate enclosure may be required.

Table 5. Available capacitors from Digikey

Manufacture	Part Number	Capacitance	Vmax	Price	Diameter	Height
Nichicon	LGR2D102MELC35	1mF	200V	$ 7.60	35mm	37mm
Vishay	MAL210212222E3	2.2mF	200V	$23.56	50mm	80mm
Cornell	450C182M160AA8	1.8mF	160V	$14.30	35mm	57mm

Figure 7. Simplified circuit diagram of passive regulated pulserFigure 7 shows a simplified circuit diagram of the passive regulated pulser scheme. The pusler has two MOSFETs. Both MOSFETs are triggered by isolated signals. The output switch will connect charged capacitor to cathode and grid when triggered and generate the required output pulse. If the output switch failed short, energy stored in capacitor bank might be dumped into the gun and damage the cathode. Another MOFET is used to protect the gun during output switch failure, which will disconnect capacitor bank from local storage capacitor when there is no trigger. The protection switch acts as an enable switch which turns on a few microseconds before the main trigger and turns off after the trigger. A one ohm resistor is connected in series with the

pulser output to limit output current during grid arc. A 50 ohm resistor connects grid and cathode of the gun and provides a discharge path for the grid when output switch is off.

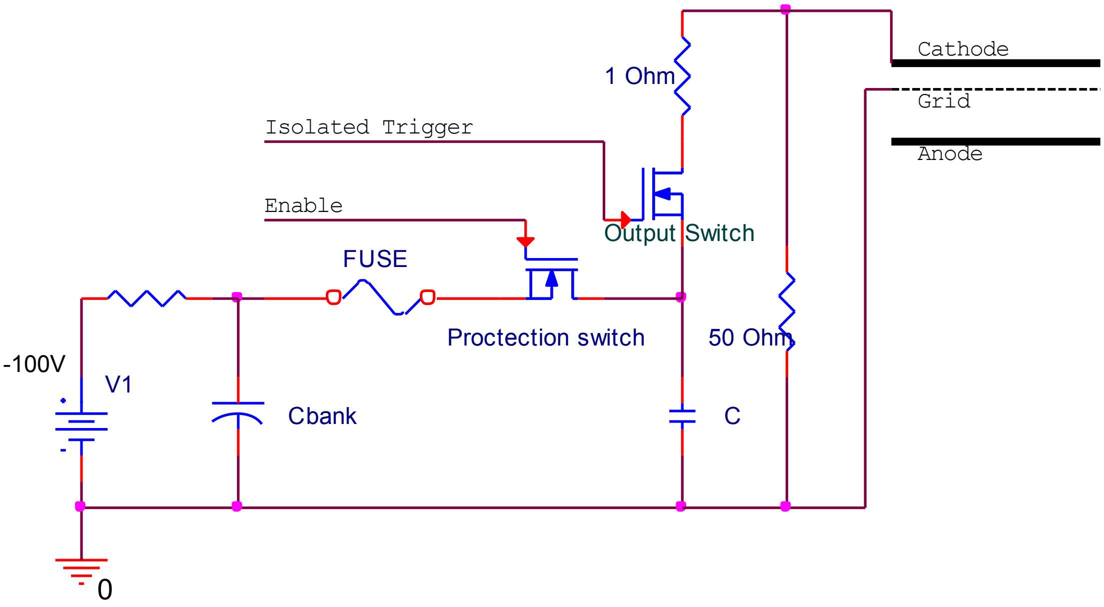

Figure 7. Simplified circuit diagram of passive regulated pulser

Figure 8 shows an optically isolated trigger board and MOSFET driver board developed in SLAC. The trigger board is rated for 1kV isolation. It can be directly used to in CLICK pulser design. The isolation unit is designed to work with a gate driver board for DE series MOSFET. For CLIC pulser application, DE275-201N25A can be used, which is rated for 200V and 25A. A new MOSFET driver board is needed if other low cost MOSFETs and driver are selected.

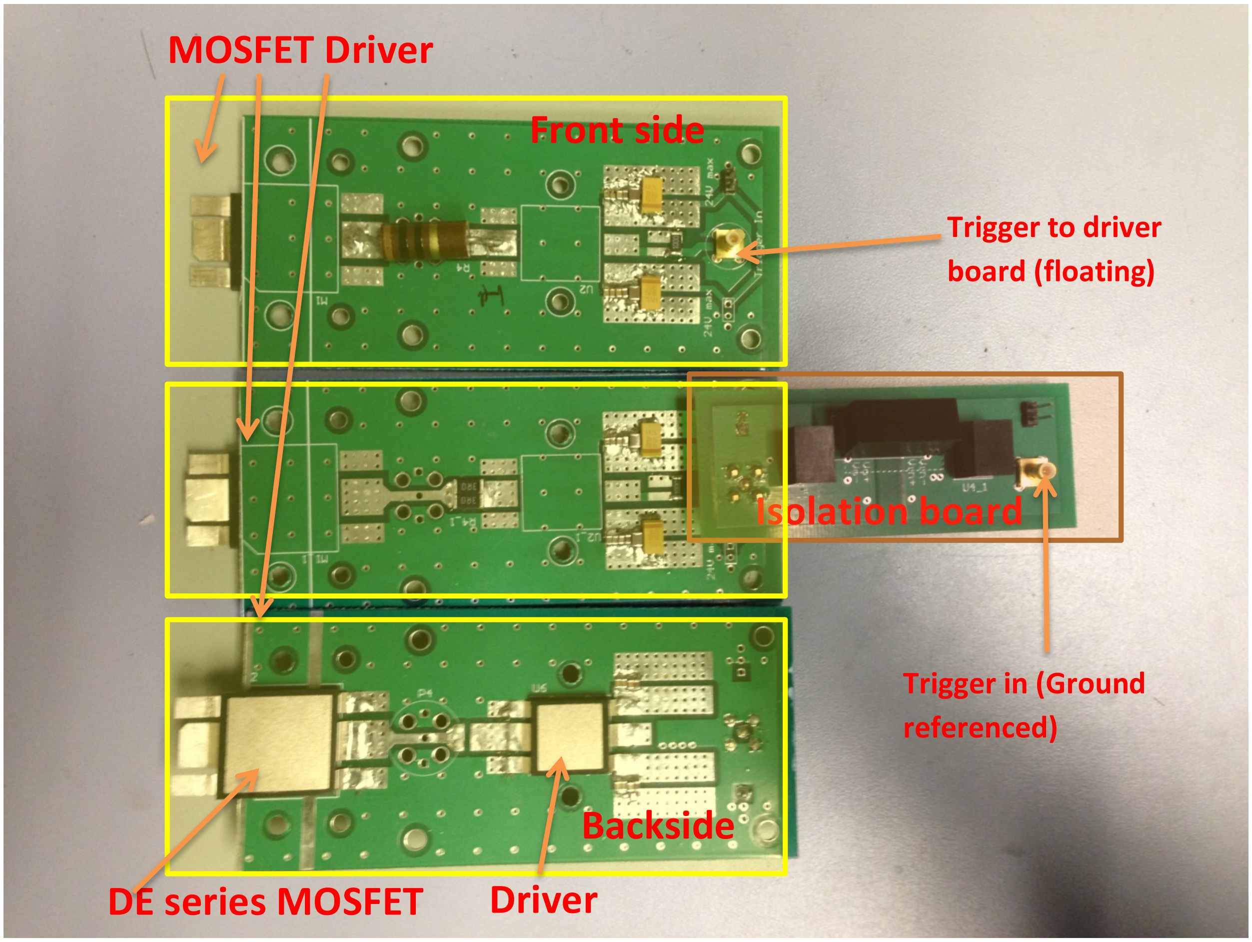

Figure 8. SLAC isolated trigger board and MOSFET driver board

The MOSFET driver and trigger isolation boards are tested in a configuration similar to Figure 7 for LCLS-II spreader kicker. In the test, local capacitor and capacitor bank were 3uF and 3mF respectively. The system was tested at -800V with a 12.5 Ohm load (64A). Output pulses had different timing compared with CLIC gun pulser requirements. The output pulse length was about 150ns and repetition rate was 333kHz (6.7% duty cycle). Statistic of 1000 consecutive pulses showed an excellent stability of peak output voltage (-866.1±0.2V or 0.02%).

Active regulation: MOSFET regulator approach

MOSFETs operate in switching mode for the passive regulation approach discussed in previous section. If the MOSFET operates in triodes mode, it will act as a variable resistor and can be used to regulate output current.

Figure 9 shows how active regulation can be implemented. In this design, the output switch operates in triodes mode. A current viewing resistor (CVR) is connected to source of the MOSFET to measure output current. The current signal from CVR is buffered by an opamp and fed into a comparator. The comparator compares measured output current with reference signal and provides an error signal. The error signal filtered by a low pass filter to generate MOSFET gate voltage.

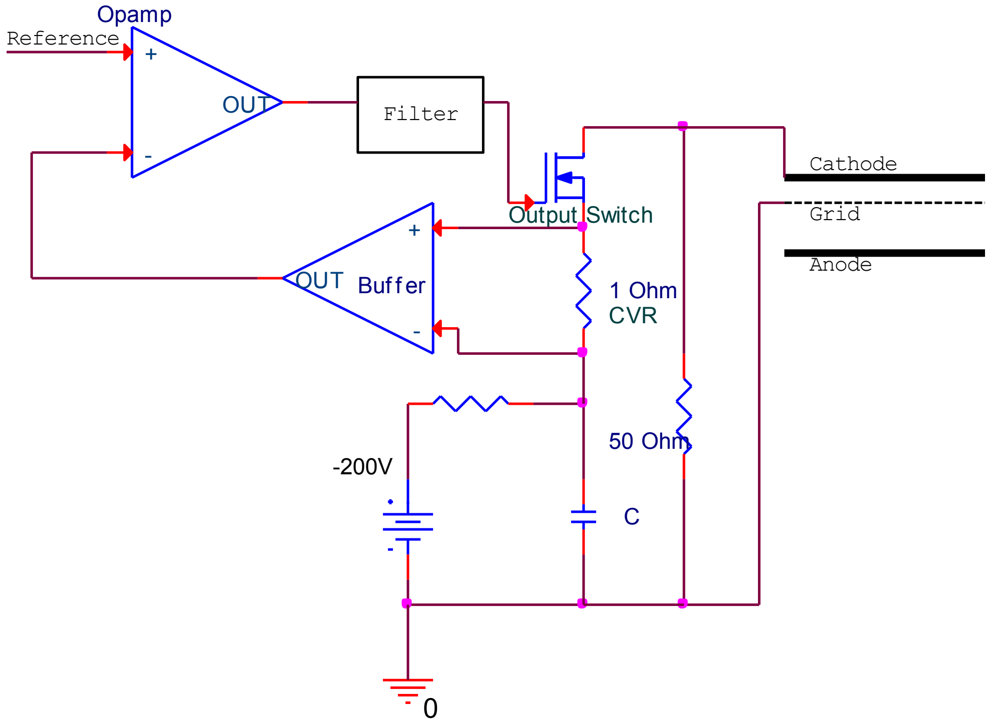

Figure 9. Simplified circuit diagram of active regulation approach

In this approach, voltage on capacitor C may decrease more than 0.1% during the 150us long pulse. At the end of the pulse, capacitor voltage should be greater than required grid voltage plus any resistive drop across CVR and MOSFET.

Assuming minimum on state resistance of the MOSFET is 1 ohm and the CVR is 1 Ohm, minimum capacitance needed for different initial voltage is plotted in Figure 10. Again, 150us long pulse and 100V grid voltage is used in calculation. It is obvious that the active regulation approach requires 100 times less capacitance compared with passive regulation approach.

MOSFET operating in triode mode has more loss than switch mode. Since output current is regulated, voltage drop across MOSFET will decrease linearly during the pulse. Thus MOSFET loss is calculated and plotted in Figure 11. Because of low duty cycle, averaging MOSFET loss is less than 1W and will not create any problem. Instantaneous power of the MOSFET can be calculated by the following equation.

$$P_{inst} = \left(V_{init} - V_{grid}\right) \cdot I_{out}$$

Further thermal analysis is needed to show the effect of instantaneous heating on switch.

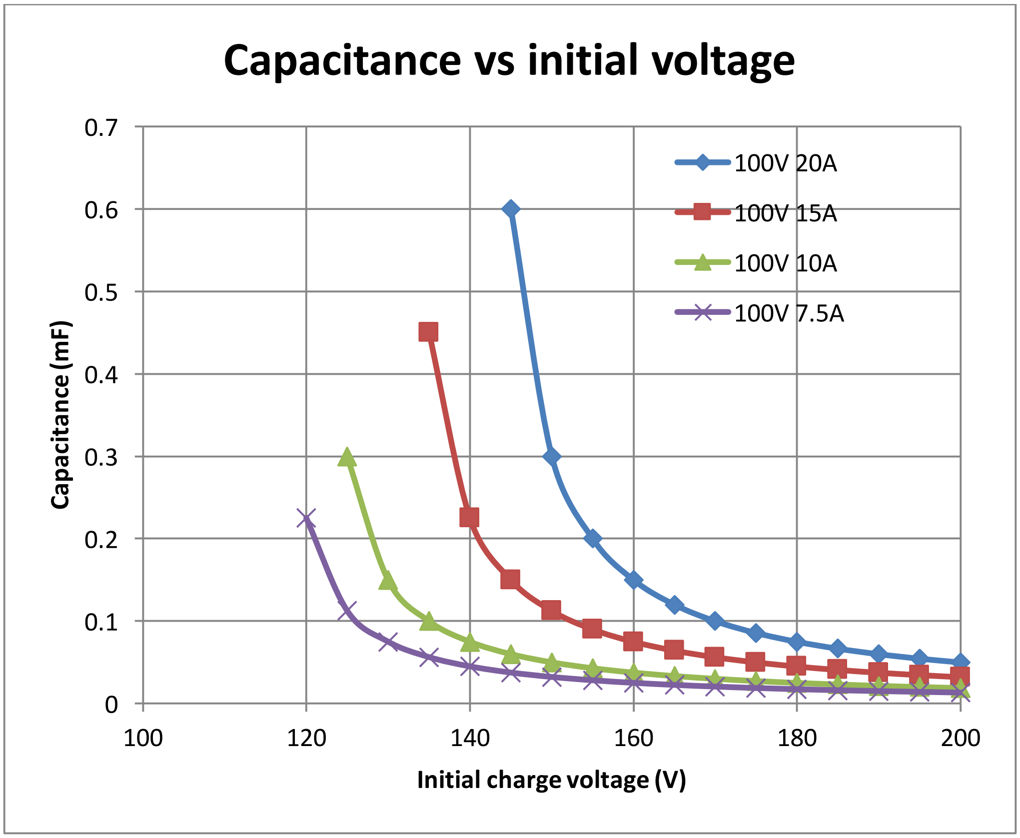

Figure 10. Minimum capacitor at different initial capacitor voltage in active regulation approach

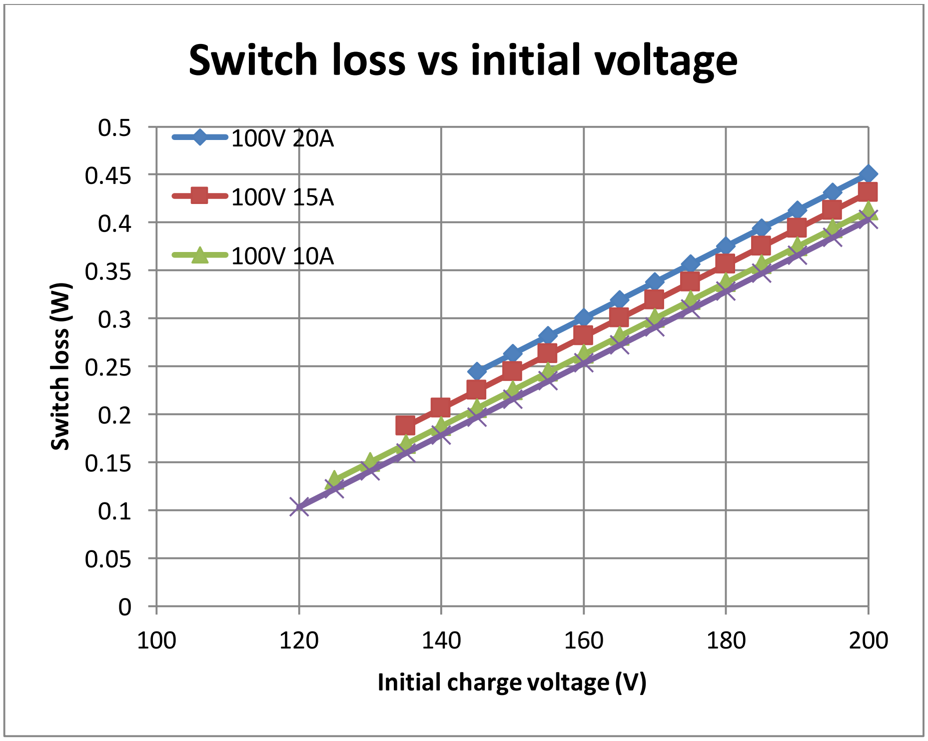

Figure 11. Switch loss at different initial capacitor voltage in active regulation approach

Conclusion

In this report, requirements of the pulser for CLIC gun are discussed. Long pulse duration combined with high output current makes regulation of output current during the pulse a challenge task. A passive regulation approach using 10s of mF capacitor bank and an active regulation approach using triode mode MOSFET are proposed. Further simulation and analysis is required to down select from these two approaches for CLIC gun pulser.

Bibliography

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