EVALUATION OF COMPONENTS FOR THE HIGH PRECISION INDUCTIVE ADDER FOR THE CLIC DAMPING RINGS

J. Holma, M.J. Barnes, CERN, Geneva, Switzerland

Abstract

The CLIC study is exploring the scheme for an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV. The CLIC damping rings will produce, through synchrotron radiation, ultra-low emittance beam with high bunch charge, necessary for the luminosity performance of the collider. To limit the beam emittance blow-up due to oscillations, the pulse generators for the damping ring kickers must provide extremely flat high-voltage pulses. The specifications for the extraction kickers of the CLIC damping rings are particularly demanding: the flattop of the output pulse must be 160 ns duration, 12.5 kV and 250 A, with a combined ripple and droop of not more than ±0.02 %. An inductive adder allows the use of different modulation techniques and is therefore a very promising approach to meeting the specifications. In addition to semiconductors working in their saturated region, semiconductors working in their linear region are needed for applying analogue modulation techniques. Simulations have been carried out to define component specifications for the inductive adder and this paper reports on the results of tests and measurements of various components.

INTRODUCTION

High energy e+e- colliders, such as CLIC [1], will be needed to investigate the TeV physics unveiled by the LHC. They would provide very clean experimental environments and regular production of all particles within the accessible energy range. To achieve high luminosity at the interaction point, it is essential that that the beams have very low transverse emittance: the Pre-Damping Ring (PDR) and Damping Ring (DR) damp the beam to an extremely low emittance in all three dimensions. The design parameters of the PDR and DR are defined by target performance of the collider, the injected beam characteristics or compatibility with the downstream system parameters: the emittances of the positrons must be damped by several orders of magnitude [2].

Kickers are required to inject beam into and extract beam from the PDRs and DRs. Jitter in the magnitude of the kick waveform causes beam jitter at the IP [2]. Thus the PDR and DR kickers, especially the DR extraction kicker, must have a very small magnitude of jitter: the 2 GHz specifications call for a 160 ns duration flattop of 12.5 kV, 250 A, with a combined ripple and droop

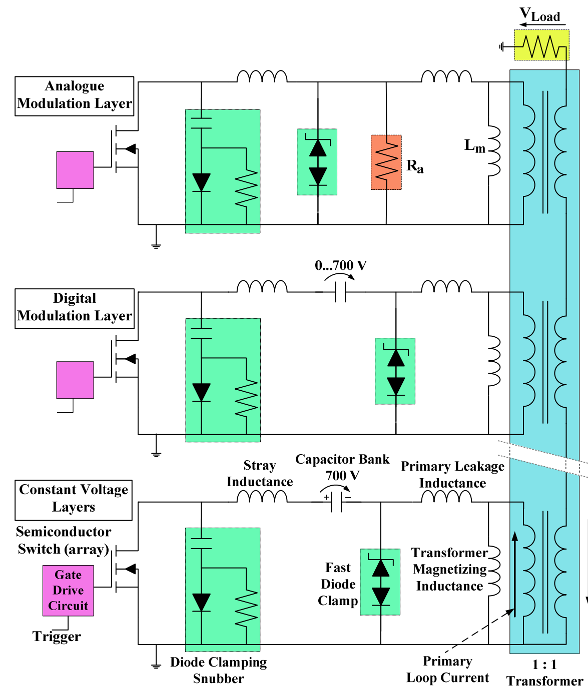

Figure 1: Schematic of an inductive adder with "constant" voltage layers, a digital modulation layer and an analogue modulation layer.

of not more than ±0.02 %, and low longitudinal and transverse beam coupling impedances [3, 4].

THE INDUCTIVE ADDER

A review of literature of existing pulse generators has been carried out and an inductive adder (Fig. 1) has been selected as a very promising means of achieving the specifications for the PDR and DR kickers [5]. The inductive adder is a solid-state modulator, which can provide relatively short and precise pulses. With a proper design of the adder it may be possible to directly meet the ripple and droop requirements of the PDR kicker [6]: studies have shown that analogue modulation may also provide a solution to meet the specifications for the DR kicker [6, 7]. Reasoning for choosing the main components of the inductive adder has been given in [6].

EVALUATION OF COMPONENTS

Pulse Capacitors

The pulse capacitors chosen for the inductive adder are manufactured by NWL Capacitors [8]; each capacitor is nominally 12 μF, rated for a peak pulse current of 280 A and a voltage of 1 kV, d.c.. The inductance of 10 pulse capacitors has been determined by individually short-circuiting a charged capacitor and measuring the resonant

ISBN 978-3-95450-115-1

frequency. A lumped element model of the pulse capacitor (Fig. 2) consists of capacitor C, inductance L and resistance R. The inductance is the sum of the inductance of the capacitor and a 4 cm wide, 6 cm long and 0.6 mm thick copper plate, which has been used to short-circuit the pins of the capacitor to each other. The resistance is the sum of ESR of the capacitor and the resistance of the copper plate. The resistance of the copper plate is relatively small.

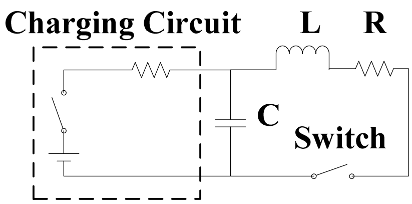

Figure 2: A lumped element model of the test circuit for the pulse capacitors.

The capacitance values were measured with a Fluke 289 digital multimeter and the output voltage, an exponentially decaying sine wave, with a Tektronix DPO5034 oscilloscope. The resonant frequency was determined from the time interval between two consecutive peaks of the output waveform, which gives the fundamental period. The resistance was computed from the damping factor of the decaying curve. The inductance was calculated using the equation:

$$L = \frac{1}{4\pi^2 f_0^2 C}$$

in which f_0 is the resonant frequency. Resistance was calculated using the equation:

$$R = \frac{2\zeta}{\sqrt{\frac{C}{L}}}$$

in which ζ is the damping factor. This is defined by

$$\zeta = \frac{-ln\frac{A}{A_0}}{\omega t}$$

in which t is elapsed time, A_0 is the amplitude of the output waveform at time point t=0, A is the amplitude at time t and ω is the angular velocity.

The results of these measurements have been summarized in Table 1. The average inductance of the ten pulse capacitors is approximately 14 nH. In the inductive adder several pulse capacitors will be connected in parallel, which further decreases the effective inductance of the pulse capacitors in the primary loop circuit. However the circuit board layout is important for minimizing the total primary circuit inductance.

Table 1: Average values and standard deviation of capacitance, inductance and resistance of 10 NWL pulse capacitors.

C/µF	σ_C/µF	L/nH	σ_L/nH	R/mΩ	σ_R/mΩ
12.12	0.15	14.35	0.40	16.66	2.73

Switching MOSFETs and IGBTs

A selection of fast switching MOSFETs and IGBTs has been tested using the IXYS IXDN409YI gate drive circuit. The load resistor was 2 Ω. The circuit diagram (Fig. 3) of the test setup is shown with a MOSFET switch but was similar for the IGBT tests.

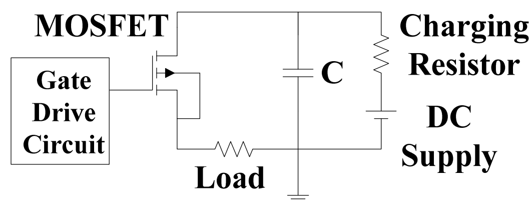

Figure 3: A test circuit for fast switching MOSFETs and IGBTs.

For the CLIC DR kicker, the desired rise and fall time of the pulse is below 100 ns. The measured rise and fall times, corresponding to amplitude change between 10% and 90% of the peak current (I_{load}), are shown in tables 2 and 3. The output pulse width was 4 µs and repetition rate 7 Hz. The rise and fall times are average values for 100 pulses, recorded using a Tektronix DPO5034. The next step for continuing these tests is to use an inductive load, which may reduce the rise times significantly, as shown in [9].

Table 2: Measured rise times T_r and fall times T_f of the tested fast switching MOSFETs.

MOSFET	U_{Cap} /V	I_{load} /A	T_r/ns	T_f/ns
IXFK20N120	59.5	19.9	87	8
IXFK21N100F	59.5	23.4	116	7
IXFK24N100F	59	24.5	119	8
IXFK26N120P	59	22.6	118	23
IXFK30N100Q2	59	24.0	118	7
APT14M120B	59.5	18.3	76	15
APT18M100B	59.3	20.9	101	14
APT1004RBN	60	9.2	8	4
APT1001RBN	60	18.5	75	15
APT12040L2LLG	60	24.1	120	13
CMF20120 (SiC)	59	26.0	149	13
IRFPG50	60	17.8	21	13

Linear MOSFETs

In order to apply analogue modulation techniques linear MOSFETs are needed for the inductive adder. In the proposed design [5], the operating voltage range for the linear switches is between 100 and 200 V, with a current capability requirement between 2 and 10 A. At

ISBN 978-3-95450-115-1

first, the linear MOSFETs were tested in a static operating mode using a d.c. power supply as the gate drive circuit. Subsequently, a linear gate drive circuit was designed, which can feed up to 2-3 A with modulation frequencies up to tens of MHz. The linearity of the dependence of the drain current I_D on the gate-source voltage U_G was of the biggest interest, and also the bandwidth of the modulation circuit.

Table 3: Rise and Fall Times of the Tested IGBTs.

IGBT	U_{Cap} /V	I_{load} /A	T_r/ ns	T_f/ns
FGL40N120ANDTU	59	26.4	150	18
FGA25N120ANTDTUX	59	26.8	296	18
HGTG27N120BN	59	26.6	358	31
IGW40N120H3	58.7	27.2	227	69
IGW40T120	59	27.4	251	253
IGW60T120	59	27.6	234	279
IRG7PH42UPbF	59.1	27.4	229	32
IRG7PH46UPbF	59	27.3	214	42
IRG7PSH73K10PbF	59	27.7	218	49
IRGP20B120U-EP	58.8	26.2	349	37
IRGPS40B120UPbF	59	26.6	267	30
IXA20IF1200HB	58.7	26.9	342	60
IXA55I1200HJ	58.7	27.1	302	144
IXDR30N120	58.6	26.9	324	34

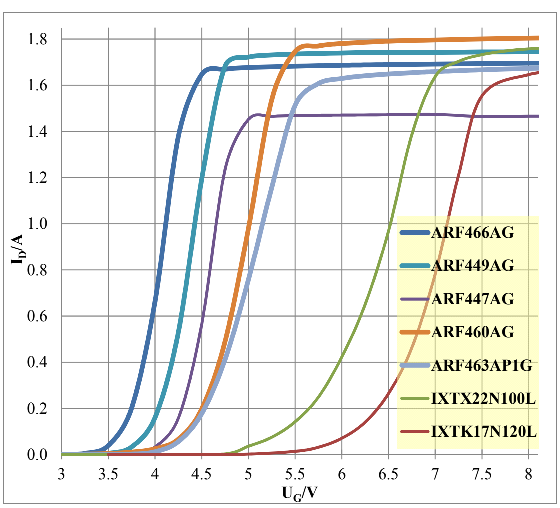

Figure 4: Current I_D as function of voltage U_G for selected linear MOSFETs (d.c. measurements).

Fig. 4 shows the measured current I_D as function of U_G for several MOSFETs. According to these tests, ARF466AG, ARF449AG, ARF460AG and ARF463AP1G are the most promising candidates for further tests because they have the largest linear range. However, more measurements are required to verify their performance in the desired voltage and frequency range.

Transformer Cores

Transformer cores are currently being evaluated for the inductive adder to determine the linearity of the B-H curve. The results of these measurements will be used to build mathematical models of the cores for simulating the magnetization current during the pulse and its contribution to the voltage droop and ripple of the output voltage of the adder. In addition the temperature stability of the cores will be measured.

CONCLUSIONS

Initial results from measurements of components, for finding the best candidates for the high precision inductive adder, have been obtained. Promising candidates for both on-off type and linear type semiconductor switches, to be used for the prototype inductive adder for the CLIC damping ring kickers, have been identified.

REFERENCES

[1] G. Geschonke, A. Chigo, "CTF3 Design Report", CERN/PS 2002-008 (RF).

[2] Y. Papaphilippou, "CLIC Damping Ring Beam Transfer Systems", March 10, 2010.

[3] Y. Papaphilippou, "Parameter Specification, EDMS #989080, Kickers for the CLIC Damping and Predamping Rings", PBS reference: 1.2._.10.

[4] Y. Papaphilippou et al, "Conceptual Design of the CLIC Damping Rings", to be publ. in proc. of this conference.

[5] J. Holma et al., "Preliminary Design of the Pulse Generator for the CLIC DR Extraction System", proc. PPC'11, Chicago, USA, June 19-23, 2011.

[6] J. Holma, M.J. Barnes, "Pulse Power Modulator Development for the CLIC Damping Ring Kickers", CLIC-Note-938, CERN, Geneva, Switzerland, April 27, 2012.

[7] J. Holma, M.J. Barnes, "Preliminary Design of an Inductive Adder for CLIC Damping Rings", proc. IPAC'11, San Sebastian, Spain, Sept. 5-9, 2011.

[8] www.nwl.com

[9] E.J. Gower, J.S. Sullivan, "Analog Amplitude Modulation of a High Voltage, Solid State Inductive Adder, Pulse Generator Using MOSFET"", Conf. Rec. of 25th Power Modulator Symposium and High-Voltage Workshop, Hollywood, CA, USA, 30 June – 3 July, 2002.