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**LABORATORY MEASUREMENTS ON TWO ± 12.5 KV INDUCTIVE
ADDERS WITH $\pm 0.02\%$ WAVEFORM STABILITY FOR CLIC DAMPING
RING EXTRACTION KICKERS**

J. Holma^{1,2}, M.J. Barnes¹, A. Chmielinska¹ and M. Pont²

¹CERN, Geneva, Switzerland

²CELLS ALBA, Barcelona, Spain

Abstract

The CLIC study is investigating the technical feasibility of an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV. Pre-damping rings and damping rings (DRs) will produce ultra-low emittance beam with high bunch charge. The DR kicker systems must provide extremely stable field pulses to avoid beam emittance increase. Each DR extraction kicker system consists of a set of striplines and two pulse modulators. Specifications for this system require that the modulator produce pulses of 900 ns flattop duration, ± 12.5 kV and 305 A, with ripple and droop of not more than $\pm 0.02\%$ (± 2.5 V) with respect to a reference waveform. Inductive adder topology has been chosen for the pulse modulators. Two full-scale, 20-layer, 12.5 kV prototype inductive adders have been designed, built and tested at CERN. This paper presents the measurements of the stability of these adders for two different waveforms: a flat-top waveform and a controlled decay waveform, the latter of which is required to generate flat-top total field for the CLIC DR extraction stripline kicker.

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J. Holma^{†1}, M.J. Barnes, A. Chmielinska, CERN, Geneva, Switzerland
 M. Pont, CELLS ALBA, Barcelona, Spain
¹also at CELLS ALBA, Barcelona, Spain

Abstract

The CLIC study is investigating the technical feasibility of an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV. Pre-damping rings and damping rings (DRs) will produce ultra-low emittance beam with high bunch charge. The DR kicker systems must provide extremely stable field pulses to avoid beam emittance increase. Each DR extraction kicker system consists of a set of striplines and two pulse modulators. Specifications for this system require that the modulator produce pulses of 900 ns flat-top duration, ± 12.5 kV and 305 A, with ripple and droop of not more than $\pm 0.02\%$ (± 2.5 V) with respect to a reference waveform. Inductive adder topology has been chosen for the pulse modulators. Two full-scale, 20-layer, 12.5 kV prototype inductive adders have been designed, built and tested at CERN. This paper presents the measurements of the stability of these adders for two different waveforms: a flat-top waveform and a controlled decay waveform, the latter of which is required to generate flat-top total field for the CLIC DR extraction stripline kicker.

INTRODUCTION

The Compact Linear Collider (CLIC) would be a high-energy electron-positron collider [1]. It could provide very clean experimental environments and steady production of all particles within the accessible TeV energy range. To achieve high luminosity at the interaction point of CLIC, it is essential that the beams have very low transverse emittance: the Pre-Damping Ring (PDR) and Damping Ring (DR) damp the beam emittance to extremely low values in all three planes. Stripline kickers are required to inject beam into and extract beam from the PDRs and DRs [2]. Jitter in the magnitude of the kick waveform causes beam displacement at the interaction point [3]. Hence, in particular, the DR extraction kicker must have excellent pulse stability (i.e. flatness).

Two full-scale prototype inductive adders for the CLIC DR extraction kicker system have been designed, built and tested at CERN. Recently, these two modulators, together with prototype striplines, have been installed and tested with beam in the ALBA Synchrotron Light Source [4].

SPECIFICATIONS FOR THE CLIC DR EXTRACTION KICKER SYSTEM

The specifications for the inductive adders for the CLIC DR extraction kicker system are shown in Table 1 [1]. Design specifications for both a 1 GHz and 2 GHz RF system were proposed: both require that the DR extraction modulator produces pulses of 12.5 kV, with $\pm 0.02\%$ stability and $\pm 0.01\%$ repeatability for the kick field [1]. The 2 GHz specifications require a 160 ns duration flat-top [1]. The 1 GHz specifications call for a burst of two 160 ns duration pulses with 580 ns between the end of the flat-top of the first pulse and the beginning of the flat-top of the second pulse. This can also be fulfilled with a single 900 ns, continuous, flat-top pulse.

Table 1: Specifications for the ± 12.5 kV Inductive Adders for CLIC DR Extraction Kicker

Output voltage	± 12.5 kV
Nominal load impedance	40.5 Ω
Nominal output current	± 309 A
Flat-top duration (excl. settling time)	160 900 ns
Waveform stability	$\pm 0.02\%$
Waveform repeatability	$\pm 0.01\%$

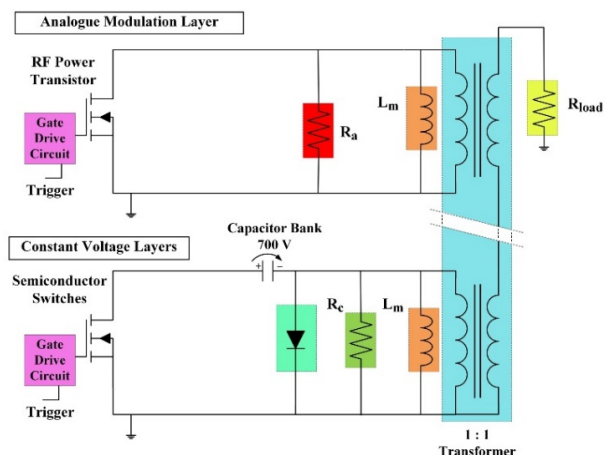


Figure 1: Schematic of an inductive adder with a single constant voltage layer and with an analogue modulation layer.

[†]janne.holma@cern.ch
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INDUCTIVE ADDERS

An inductive adder (Fig. 1) is a solid-state modulator, which can provide relatively short and precise pulses, and hence it has been selected as the most promising means of achieving the specifications for the DR kickers [5]. An early reference about design principles of an inductive adder is given in [6] and an extensive summary of previous developments of inductive adders at Lawrence Livermore National Laboratory is given in [7], with examples of using modulation techniques for trimming output waveforms. More recent research on inductive adders, also called inductive voltage adders or linear transformer drivers in the literature, have been carried out for Pockels Cells drivers for the National Ignition Facility [8], fast kicker systems at Lawrence Berkeley National Laboratory [9] and industrial applications of pulsed power [10].

In total five prototype inductive adders for the CLIC DR kicker systems have been designed and built at CERN. The reasoning for choosing the main components of the prototype inductive adders has been given in [11, 12]. Operation of the passive and active modulation layers has been verified with measurements in [12, 13]. Evaluation of magnetic cores for the full-scale, 12.5 kV, prototype inductive adders was presented in [14]. Two papers [15, 16] presented measurements on the first 20-layer, full-scale, prototype inductive adders, with analogue modulation applied to generate either a flat-top pulse or a controlled decay waveform. In these papers, the best measured stability for a flat-top pulse and for a decay waveform was $\pm 0.02\%$ over 160 ns at 10 kV. In the measurements shown in [17], the stability of $\pm 0.02\%$ was achieved over 900 ns for a flat-top pulse at 10 kV. This paper, together with [4], is a continuation of these studies.

STRIPLINE KICKER

A prototype stripline kicker for the CLIC DR extraction kicker system has been designed and built [2]. Simulation of the striplines have shown that, in order to achieve the required stability (flatness) for the total of the deflecting magnetic and electric fields, the waveform for driving the striplines should be a “controlled decay waveform”, as shown in [18], instead of a “flat-top” pulse. Hence, the shape of the inductive adder output waveform must be compared to a simulated, optimally shaped, pulse waveform instead of a flat-top pulse. Characterisation of the prototype striplines, including beam-based measurements of longitudinal and transverse beam coupling impedance, transverse field homogeneity and longitudinal field stability, were carried out at ALBA Synchrotron Light Source in 2018 and 2019 [4, 19-21].

MEASUREMENTS

Measurement Set-up

Measurements reported in this paper were carried out with two prototype inductive adders with either 18 or 19 constant voltage layers, and a single analogue modulation layer installed, and one spare constant voltage layer in the

case of measurements with 18 constant voltage layers (Fig. 2). The primary circuit of each constant voltage layer consisted of a single printed circuit board (PCB) with three or four current branches powered. Each current branch consisted of either a single NWL T00216, 12 μF , [22] or a Leclanché PPM-4 170-23.0, 12 μF [23], pulse capacitor, and an APT12057LFLL [24] MOSFET. Each cell of the inductive adder was equipped with two Finemet FT-3L type magnetic cores [14, 25]. The nominal maximum output voltage of the set-up was 12.5 kV. The output waveform was recorded with a Rohde & Schwarz RTO1004 oscilloscope [26], which has a specified resolution of 14 effective bits in the required bandwidth, 100 MHz. The primary circuit of the analogue modulation layer consisted of a 2.4 Ω resistor in parallel with a radio-frequency power MOSFET, type ARF463AP1G [24].

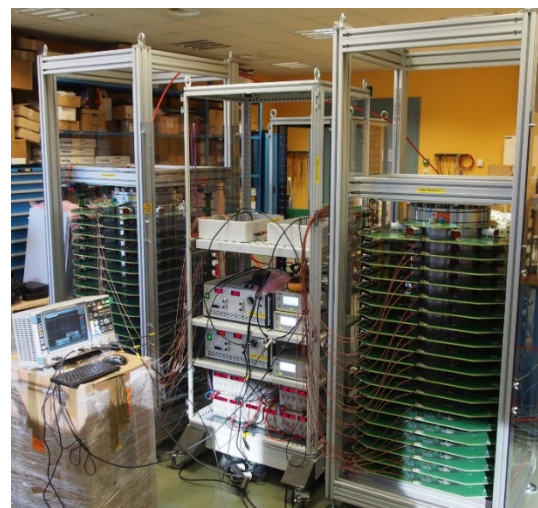


Figure 2: Two 12.5 kV, 20-layer, prototype inductive adders (left and right) with trigger amplifiers, power supplies and signal generators (middle).

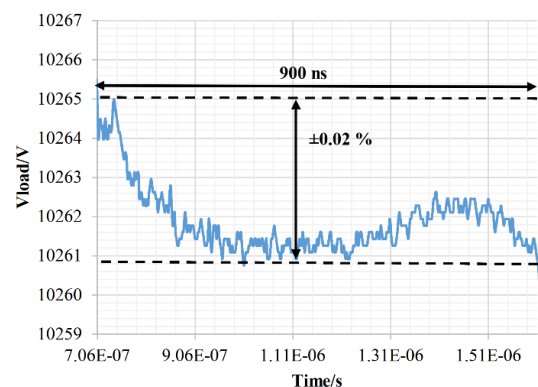


Figure 3: Measured flat-top waveform of the prototype inductive adders with active analogue modulation. The curve is an average of 1000 pulses.

Measurement of a Flat-top Pulse

In this measurement, a flat-top pulse (Fig. 3) was generated and active analogue modulation was applied. The measured flat-top stability was $\pm 0.02\%$ (± 2.0 V) over

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900 ns. This fulfils the stability requirement for the 1 and 2 GHz specifications for the CLIC DR extraction kicker system, however at 80 % of the nominal voltage. The waveform shown in Fig. 3 is an average of 1000 measured pulses: averaging is needed to achieve the required resolution of the measurement. This measurement was repeated with both negative and positive polarity of a prototype inductive adder with the same measured stability.

Measurement on a Controlled Decay Waveform

Figure 4 shows a simulated optimum controlled decay waveform (green, dashed) with error margins for stability, i.e. $\pm 0.02\%$ (black, dashed) and a measured waveform (blue). The measured load voltage, an average of 1000 pulses, is within $\pm 0.02\%$, over 900 ns, with respect to the simulated reference waveform and this fulfils both the 1 and 2 GHz specifications for the CLIC DR extraction kicker system, at approximately 80 % of the nominal voltage. Stability requirements were met with measurements on negative and positive pulses.

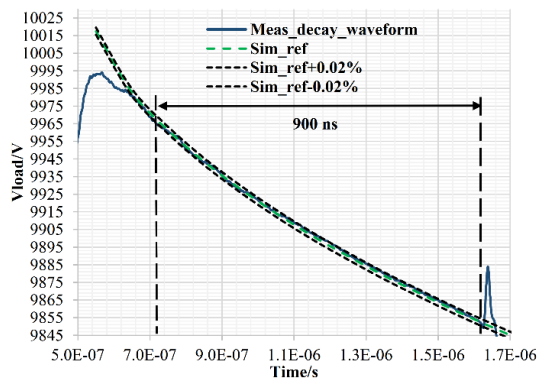


Figure 4: Measured decay waveform (blue) of the prototype inductive adders with active analogue modulation, with simulated reference waveform (green, dashed) and $\pm 0.02\%$ error margins (black, dashed). The measured waveform is an average of 1000 pulses.

Stripline Conditioning, Reliability and Maximum Tested Voltage

Before beam-based measurements on the complete prototype extraction kicker system at ALBA, reported in [4], the prototype striplines were conditioned with the prototype inductive adders in the laboratory (Fig. 5). The striplines were in vacuum, as in the final installation in the beamline, and they were tested by pulsing both striplines with opposite polarities up to ± 10 kV. Striplines were pulsed at 3.125 Hz for over 10k pulses. No issues were detected with the inductive adders, striplines, or vacuum during these tests.

In total over 8 million pulses have been generated with the two prototype inductive adders at 10 kV at 1...10 Hz, without any major issues with the hardware. The maximum voltage tested with the prototype inductive adders has been 12 kV until now. At 6 kV, one adder has been tested continuously at 50 Hz for 13 million pulses without any issues. Testing time at voltages above 10 kV has been limited by

issues with high-voltage connectors and faulty PCBs. Approximately one half of the received primary PCBs have operated at the nominal 700 V with all four branches. However, in the other half, one of the branches had to be disconnected to have stable operation as a result of an unidentified issue with the PCB cards. To avoid possible breakdowns, the maximum operation voltage was limited to ± 10 kV before testing the prototype inductive adders in the beamline. Primary PCBs have also been tested in representative fault conditions, e.g. with a short-circuit load, saturation of a magnetic core and a fault in the trigger system [27].

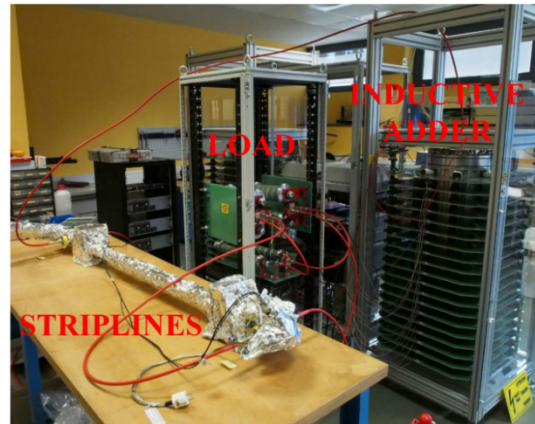


Figure 5: Test setup for conditioning of the CLIC DR stripline consisting of two inductive adders (1st on the right, 2nd behind the load), terminating load (middle), and striplines (left).

SUMMARY AND ON-GOING WORK

Laboratory measurements presented in this paper and beam-based measurements presented in [4] have confirmed that $\pm 0.02\%$ stability specifications for the CLIC DR extraction kicker system are very probably achievable. The measured stabilities are an order or magnitude better than in typical kicker systems used for accelerators. However, in all measurements shown in this paper, averaging has been applied to increase the resolution of the measured voltage: the stability of a single kick or voltage waveform was not measured here.

In the future, one of the prototype inductive adders will be equipped with an additional eight layers, in a series connection of two inductive adders, to test the feasibility of a 12.5 kV/17.5 kV inductive adder for the combined CLIC DR extraction and dump kicker system [27]. This is also expected to meet the specifications for the CLIC DR injection and the CLIC PDR injection and extraction kicker modulators [1]. An inductive adder stack with active analogue modulation layers only can also be used as a pulse conditioner [27, 28], and it can be connected to other type of modulators, e.g. a Marx generator, stacked switches, or a pulse-forming line or network [27]. The inductive adder technology is also seen as a promising technology for use in both existing kicker systems [29] and possible future kicker systems at CERN, e.g. for injection systems of the Future Circular Collider [30, 31].

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