MEASUREMENTS ON MAGNETIC CORES FOR INDUCTIVE ADDERS WITH ULTRA-FLAT OUTPUT PULSES FOR CLIC DR KICKERS

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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. The CLIC pre-damping rings and damping rings (DRs) will produce ultra-low emittance beam with high bunch charge. To avoid beam emittance increase, the DR kicker systems must provide extremely flat, high-voltage, pulses. The specifications for the DR extraction kickers call for 160 ns duration flattop pulses of ±12.5 kV, with a combined ripple and droop of not more than ±0.02 % (±2.5 V). An inductive adder is a very promising approach to meet the specifications. Two five layer, 3.5 kV, prototype inductive adders have been built at CERN, and used to test passive and active analogue modulation methods to compensate droop and ripple of the output pulses. Recently, magnetic core materials and full-scale magnetic cores have been evaluated for the 12.5 kV prototype inductive adders. These results are presented in this paper and conclusions are drawn concerning the design of the full-scale prototypes.

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, 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 jitter at the interaction point [3]. Hence, in particular, the DR extraction kicker must have a very small magnitude of jitter: the 2 GHz specifications call for a 12.5 kV pulse of 160 ns duration flat-top, with a combined ripple and droop of not more than ±0.02 % [1].

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 the most promising means of achieving the specifications for the DR kickers [4]. The inductive adder is a solid-state modulator, which can provide relatively short and precise pulses. With a careful design of the adder, it may be possible to directly meet the ripple and droop requirements of the PDR kicker and analogue modulation may provide a means to meet the demanding specifications for the DR kicker [5, 6].

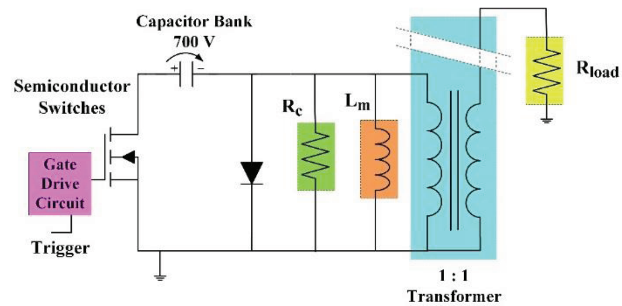

Figure 1: Schematic of an inductive adder with a single constant voltage layer with core loss resistance R_c and magnetizing inductance L_m.

The reasoning for choosing the main components of the inductive adder has been given in [6]. Two 5-layer prototype inductive adders have been assembled at CERN. The design parameters and the initial results for these pulse modulators were presented in [7] and [8]. The prototype inductive adders have been equipped with an analogue modulation layer, which can be used to compensate the droop and ripple of the output waveform. Operation of the passive and active modulation layers has been verified with measurements and the results have been presented in detail in [9-11]. This paper presents the results of evaluating magnetic core materials for the inductive adder, with extremely high flat-top stability, and it is a continuation of the study presented in [11].

EVALUATION OF THE CORE MATERIAL

Simple Model of a Magnetic Core

Figure 1 shows a schematic of a single layer of an inductive adder including two parasitic elements, namely the core loss resistance R_c and the magnetizing inductance L_m. The values of these parameters have been determined for the evaluated cores by measuring the primary loop current of a single layer using a current transducer. In these measurements, only a single current branch per layer was switched on, i.e. all the primary current flowed through the current transducer. Six different core materials were evaluated. The dimensions of the evaluated magnetic cores are shown in Table 1.

Desired Characteristics for the Core Material

The desired characteristics for the core material, for an inductive adder with extremely high flat-top stability, are the following: the magnetizing inductance L_m and the core loss resistance R_c should be as high as possible. The

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remnant field, marked as B_{r+} and B_{r-} in Fig. 2, should be as low as possible. The reason for this is that biasing will not be applied to the magnetic core before the pulse, i.e. only the B-H flux swing from B_{r+} to saturation flux density B_{s+} is available. The reason for not biasing the cores is that a bias circuit both adds complexity to the adder and typically degrades the stability of both the flat-top and intra-pulse voltage, as was explained in [12].

A high L_m keeps magnetizing current low and, therefore, the voltage droop of the output pulse is smaller than with a lower L_m. In [9], it was shown that low magnetizing inductance may be the main contributor to the droop of the output waveform and this droop cannot necessarily be decreased by adding more capacitance per layer to the inductive adder. In addition, the permeability of the core should also be linear during the pulse, i.e. the magnetic field B should change linearly as function of the magnetizing field H. For this reason, a linear B-H curve (blue, dashed, curve in Fig. 2) is more desirable than an S-shaped B-H curve (black, solid, curve in Fig. 2).

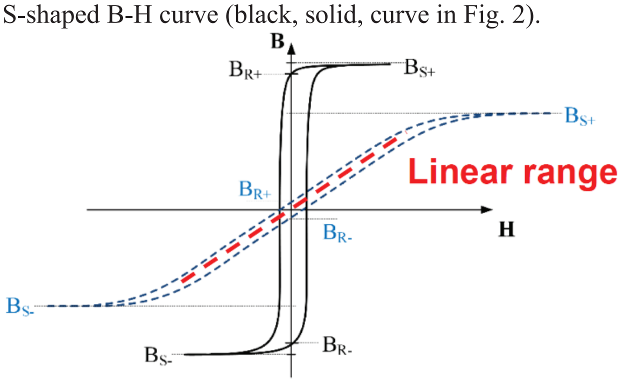

Figure 2: Examples of a S-shaped B-H curve and a linear B-H curve.

The core loss resistance R_c should be as high as possible. The lower the value of R_c, the higher the loss current and, therefore, the droop of the capacitor voltage during a pulse. A higher core loss current also gives higher losses in semiconductor switches. Also, in the inductive adder design, the cores are placed inside a metal housing. In order to keep the temperature of the cores below the maximum operational temperature, typically 100°C, the estimated maximum allowed power loss is a few Watts per core.

Measurements on Magnetic Cores

The measurements were carried out with a prototype inductive adder. The primary side of a single layer of an adder, built on a printed circuit board (PCB), was modified to consist of one current branch, i.e. a single capacitor and a single semiconductor switch. The current path on the PCB was also modified to include a loop, made of a thin sheet of copper, through which the current measurement probe was inserted (Fig. 3). The primary current was measured either with a Rogowski coil transducer [13] or with a Tektronix current probe [14].

Figure 4 shows an example of a measured primary loop current I_{pr}. The R_c and L_m can be estimated from the following equations:

$$R_c = \frac{V_c}{I_0}$$

$$L_m = \frac{V_c \times \Delta t}{\Delta i_{Lm}}$$

In these equations, V_c is the voltage across the core, I_0 is the initial current "step" of the primary loop, i.e. after rise time, and Δi_{Lm} is the change of the magnetizing current during a time interval Δt.

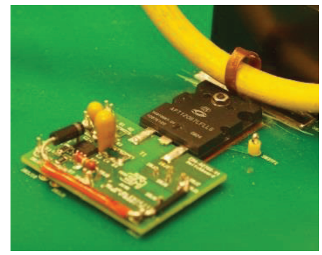

Figure 3: Set-up to measure primary current of an inductive adder, with a copper loop, using a Rogowski coil (yellow cable).

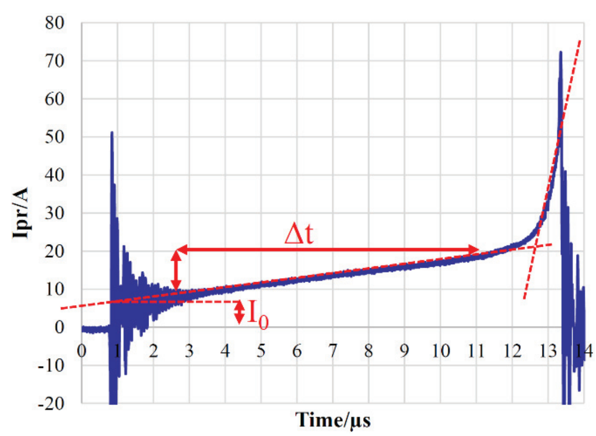

Figure 4: An example of measured magnetizing current of a single layer of an inductive adder.

Characteristics of the Evaluated Cores

Six different core materials were evaluated. The dimensions of the cores are given in Table 1 and a summary of the measurements in Table 2. In Table 1, OD is the outer diameter, ID is the inner diameter, H is the height and Ac_{eff} is the effective cross-sectional area of a core. In Table 2, I_b is the applied DC biasing current and t_p is the pulse duration. The pulse was terminated when the measured primary current reached 100 A.

Cores A1 and B1 are made of nanocrystalline material. They have the highest core loss resistance and relatively high magnetizing inductance, which remained constant for a significant portion of the total pulse duration. This means that the B-H curves for these cores are linear. Other cores were made of amorphous material. Cores C1, D1 and D2 have S-shaped B-H curves and core D3 a square-shaped B-H curve: the remnant fields of these cores are

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relatively high and they cannot be used without biasing. Cores D1-D3 also have significantly lower core loss resistances than cores A1 and B1, which means higher losses. Figure 5 shows the load voltage of an inductive adder with a single layer, equipped with the evaluated cores. The capacitors of the layer were initially charged to 250 V and the cores were not biased before the pulse.

Table 1: Dimensions of the Evaluated Magnetic Cores

Core	ID (mm)	OD (mm)	H (mm)	Ac_{eff} (cm^2)
A1	91	160	25.0	5.82
B1	95	135	28.5	2.85
C1	92	160	30.0	8.67
D1	91	160	25.4	6.13
D2	91	160	25.4	6.13
D3	94	160	32.0	7.39

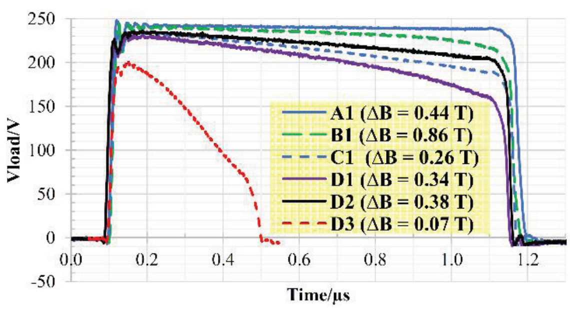

Figure 5: Measured load voltage of a single layer of an inductive adder with each evaluated core, without biasing.

EVALUATION OF MAGNETIC CORES FOR 12.5 KV INDUCTIVE ADDERS

Based on the results of the measurements, shown in Table 2 and Fig. 5, core material A1 was chosen for the full-scale prototype inductive adder. This material is Finemet FT-3L, manufactured by Hitachi-Metals [15]. The dimensions of the full-scale cores were: OD: 256 mm, ID: 156 mm and height 25 mm. The full-scale cores were evaluated with the same technique as described above. In order to have adequate cross-sectional area, for achieving the required volt-second product, two cores are needed per layer. Measurements were carried out for a single layer of an inductive adder with two stacked cores.

Figure 6 shows the measured primary current for seven 2-core set-ups. The initial capacitor voltage of a layer was 700 V and the pulse duration was 2 µs. The magnetizing inductance L_m, computed for a 1 µs pulse duration, is 57.5±6.5 µH for the set-ups with 2 cores. The total core loss resistance is approximately 140 Ω for each 2-core set-up. Matching of the core pairs might be required, in order to ensure similar pulse waveforms for layers. In Fig. 6, the set-up with C5 and C6 has the highest L_m, 64 µH, and set-up C9 and C10 the lowest L_m, 51 µH. The matched 2-core set-up C5 and C10 has L_m of 55 µH and the set-up C6 and C10 L_m of 58 µH. The measured magnetizing inductances of the single cores, for 1 µs pulse duration, were 30 µH for C5, 25 µH for C10, 35 µH for C6 and 25 µH for C9.

Table 2: Characteristics of the Evaluated Magnetic Cores

Core	I_b (A)	t_p (µs)	L_m (µH) min|max	R_c (Ω)
A1	0	0.9	110 | 0.9	25.0
	8	1.7	40.1 | 1.9	25.1
B1	0	0.6	4.9 | 0.8	25.3
	8	1.1	16.0 | 1.4	24.8
C1	1	3.5	7.4 | 3.8	10.5
	8	3.8	n/a | 10.9	10.6
D1	1	2.1	n/a | 5.2	8.4
	8	2.6	36.2 | 3.3	8.3
D2	1	1.1	12.7 | 7.4	8.4
	8	2.4	29.2 | 10.1	8.6
D3	1	3.3	n/a | 39.5	6.2
	8	3.5	n/a | 39.4	6.3

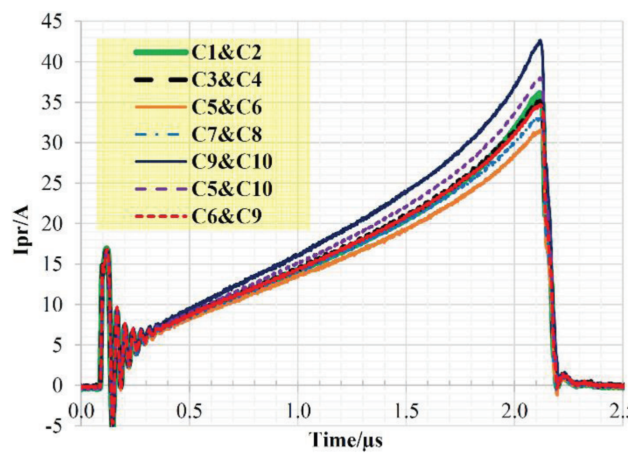

Figure 6: Measured primary current of a single layer with two full-scale magnetic cores for seven evaluated core set-ups.

CONCLUSION AND FUTURE WORK

Magnetic core material has been evaluated for the inductive adders for the CLIC DR kicker systems, which require extremely high flat-top stability. Full-scale cores, made of the material selected from tests, have been received and further testing has commenced. The magnetizing inductance and core loss resistance have been measured for seven different core set-ups. Next, the cores will be installed in a full-scale, 20-layer, 12.5 kV prototype at CERN. This prototype adder will be used to demonstrate the feasibility of the CLIC DR kicker systems with the required flat-top stability.

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