

# Measurements on +/-12.5 kV Inductive Adders with +/-200 ppm Pulse Flatness over 900 ns for CLIC Damping Ring Kickers at CERN

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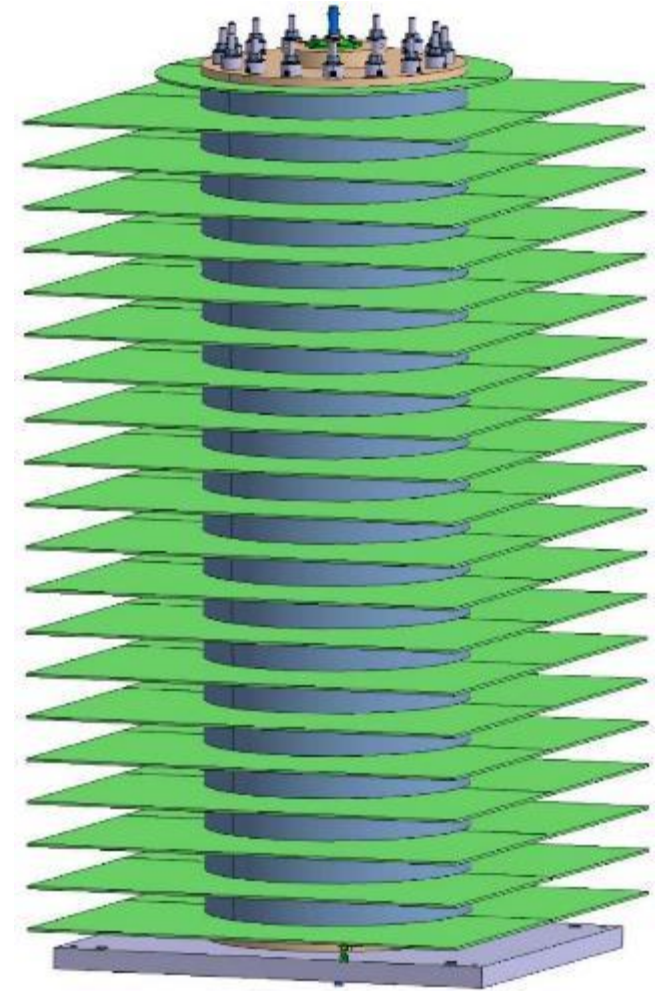
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Contributions from M.J. Barnes<sup>1</sup> and C. Belver-Aguilar<sup>1</sup>

# Outline

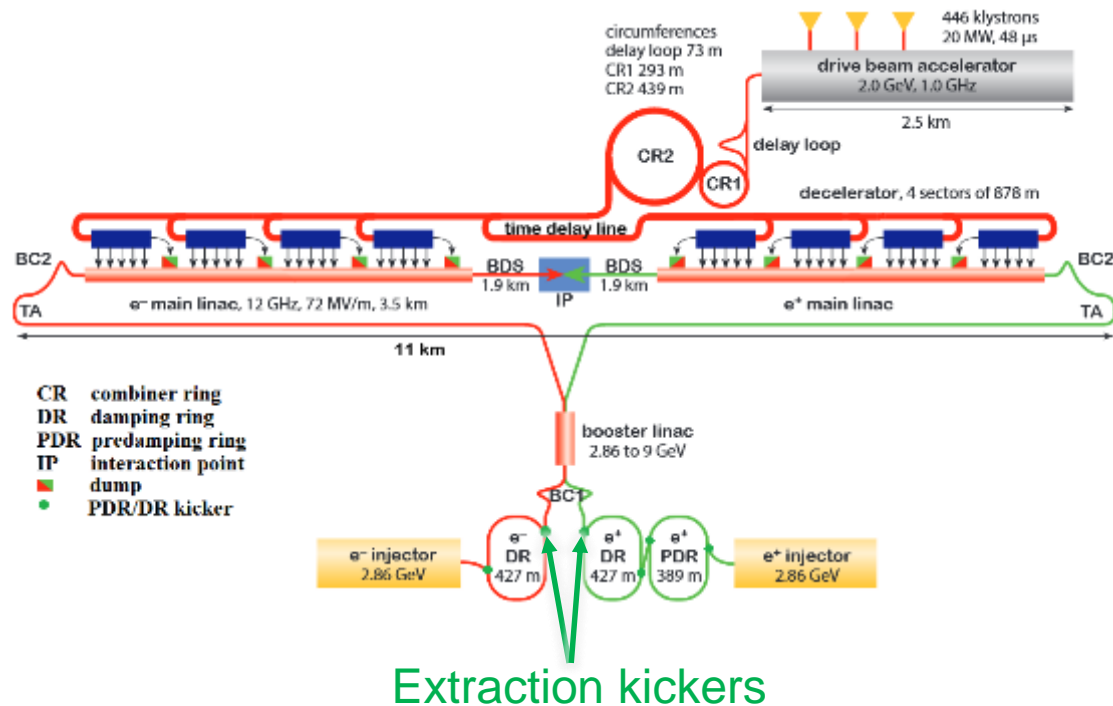
- Background and Motivation
  - Compact Linear Collider (CLIC)
  - Specifications for CLIC DR Extraction Kicker Modulator
- Inductive Adder
  - Schematic and Features
  - Methods to Improve the Pulse Flat-top Stability
- Prototyping and Measurements
  - 12.5 kV, 20-layer, "Full-scale", CLIC DR Extraction Kicker Prototype Inductive Adder
  - Measurements on Flat-top Pulse
  - Measurements on Controlled Decay Waveform for the CLIC DR Stripline Kicker.
- Summary and Future Work



# Compact Linear Collider (CLIC)

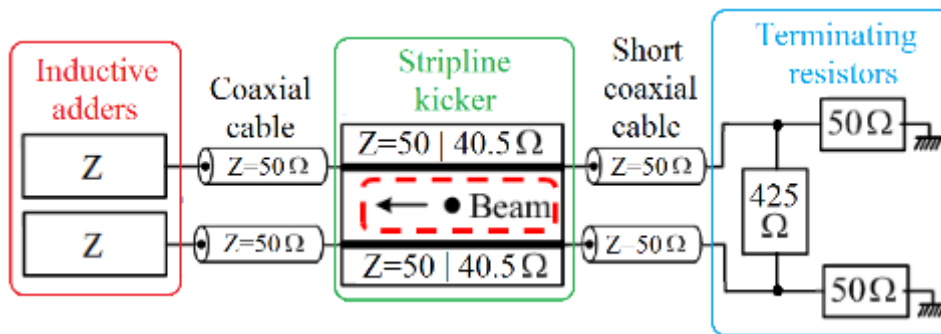


- Electron-positron collider, up to 48 km (3 TeV) long linear accelerator.
- Several stages: Injectors, Pre-Damping (PDR) and Damping Rings (DR) and main linear accelerators.
- A crucial parameter to be minimized is the beam emittance ("cross-sectional area of the beam").
- The emittance of the beam is reduced by PDRs and DRs (synchrotrons): wiggler magnets cause particles to emit synchrotron radiation (photons) and lose energy of both transversal and longitudinal momentum components. The momentum loss is compensated by accelerating the particles (by RF cavities), which increases the longitudinal momentum. As result, the energy of the particle beam is preserved, but the emittance of the beam is decreased.
- Each bunch passes through the linear accelerator only once: any variation of the electric and/or magnetic field of the **DR extraction kicker** would cause the emittance to increase.

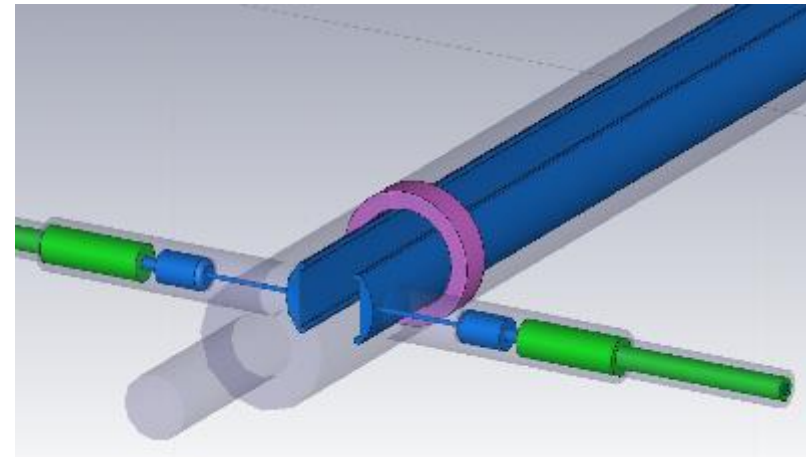


CLIC layout for 380 GeV baseline

# Specifications for the CLIC DR Extraction Kicker Modulators: *Waveform Stability & Repeatability*



Simplified schematic of a CLIC DR stripline kicker system

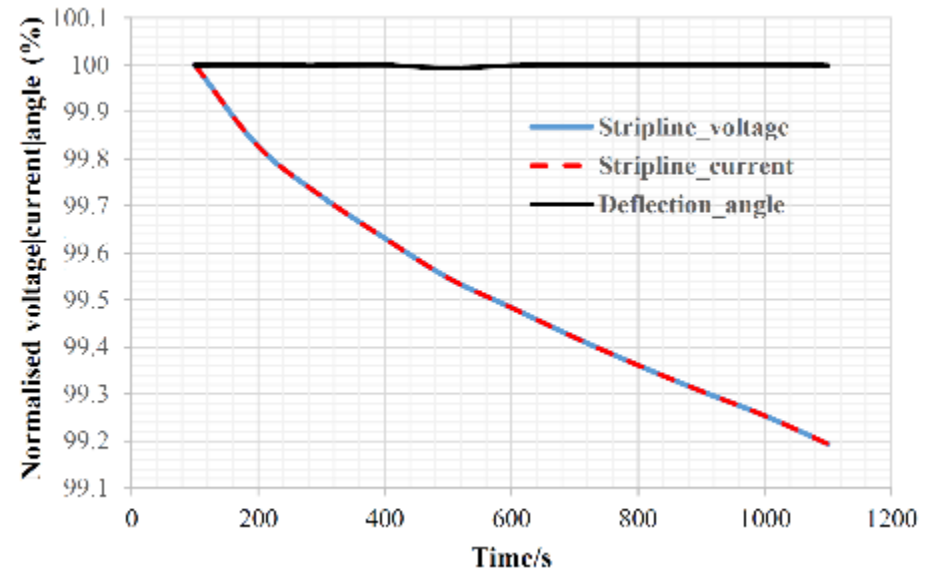


3D model of the CLIC DR stripline electrodes

- **Stripline kicker: two electrodes, powered with opposite polarities**
- **Both electric and magnetic fields deflect the beam.**
- **Impedances of the striplines are  $50 \Omega$  when "off" and  $40.5 \Omega$  when "on": both modes are matched with a terminating resistor network.**
- **The total deflecting angle for particles in each bunch during a single kick should be the same.**
- **According to optimization studies of the CLIC DR prototype stripline kicker (by C. Belver-Aguilar), the impedance of the kicker does not remain unchanged during the pulse: in order to generate the same deflection for each bunch, the voltage and current need to be modulated.**
- **The optimum waveforms for two stripline electrodes are identical "controlled decays": these generate a constant "flat-top" for total deflecting field.**

# Specifications for the CLIC DR Extraction Kicker Modulators: *Waveform stability & repeatability*

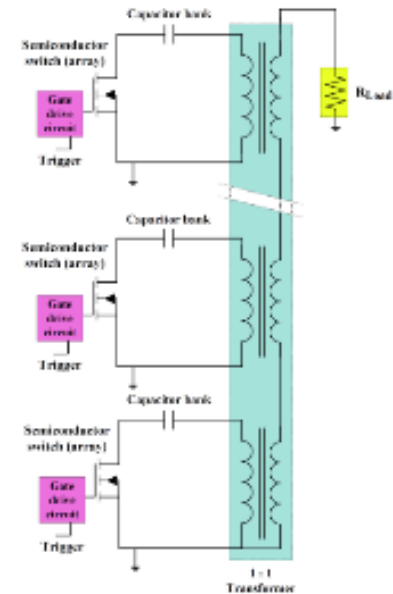
	CLIC DR (1 GHz   2 GHz)
Pulse voltage (per Stripline)	$\pm 12.5$ kV
Stripline pulse current [40.5 $\Omega$ load]	$\pm 309$ A
Repetition rate	50 Hz
Pulse waveform duration *900 ns = 160 ns + 580 ns gap + 160 ns	$\sim 160$ ns   $\sim 900^*$ ns
<b>Waveform repeatability</b>	$\pm 1 \times 10^{-4}$ ( $\pm 0.01$ %)
<b>Waveform stability</b>	$\pm 2 \times 10^{-4}$ ( $\pm 0.02$ %)
Voltage rise/fall time	< 1000 ns



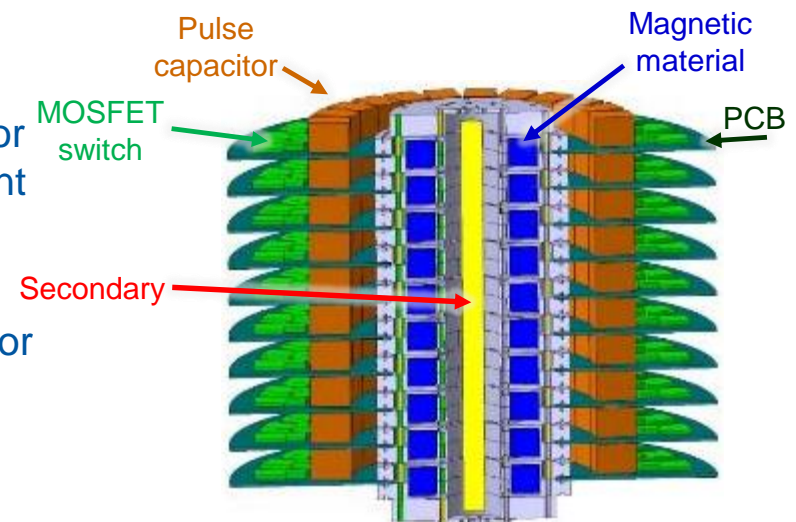
- The required waveform is a controlled decay.
- Definitions for waveform parameters
  - Repeatability: difference of amplitudes of any two waveforms during the pulse (160 | 900 ns)
  - Stability: difference between the optimum, simulated, waveform and a generated waveform at any time point during the pulse
- **Extremely tight requirements for waveform stability and repeatability!**
- For rise/fall times,  $\leq 100$  ns desired

# Inductive Adder

- Many primary “layers”, each with solid-state switches
- The output voltage is approximately the sum of the voltages of the primary constant voltage layers
- + The output voltage can be modulated during the pulse by passive/active analogue modulation.
- + Possibility to generate positive or negative output pulses with the same adder: the polarity of the output pulses can be easily changed by grounding the other end of the output of the adder
- + All control electronics referenced to ground potential.
- + Built-in fault tolerancy and redundancy: if one switch or layer fails, the adder still gives full voltage or a significant portion of the required output pulse (good for the machine safety).
- + Modularity: the same design can potentially be used for kickers with different specifications (CLIC PDR & DR kicker modulators, extraction + dump kicker)



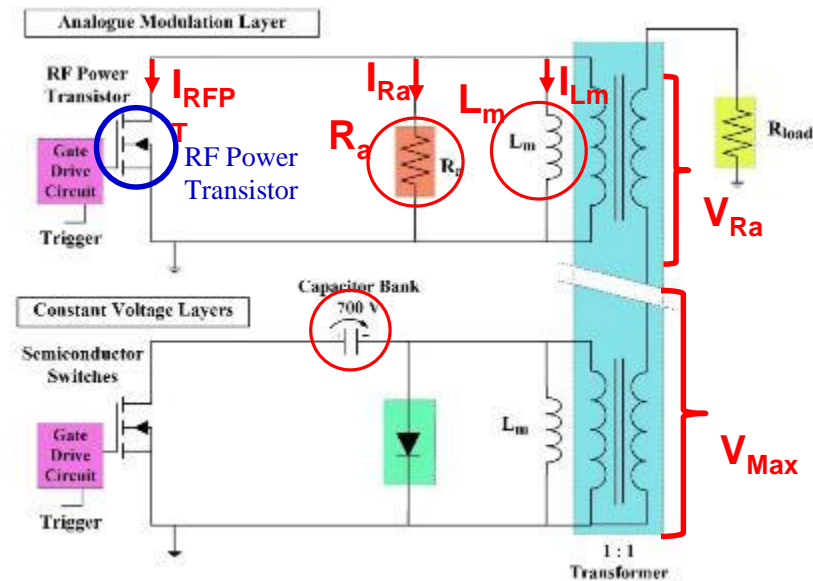
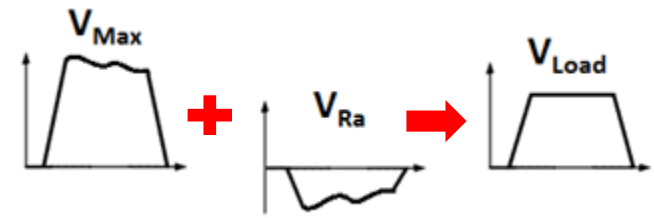
Inductive adder





# Improving the Waveform Stability: Active Analogue Modulation

- Droop and ripple of the output pulse can be compensated with an active analogue modulation layer
- Operation principle: the primary of the analogue modulation layer is effectively in series with the load. The primary consists of resistor  $R_a$  in parallel with magnetizing inductance  $L_m$  and an **RF power transistor**.
- The load voltage is the sum of the voltages across all of the layers ( $V_{Max} + V_{Ra}$ )
- **Active mode:** The voltage across  $R_a$ , i.e. across the analogue modulation layer, can be controlled by modulating the current through the RF power transistor.
- **Passive mode** (RF power transistor is off): During the pulse, current through  $L_m$  increases, which causes current through  $R_a$  to decrease. Therefore, voltage over  $R_a$  decreases, which can compensate for a reduction in the primary voltage (i.e. droop) of the other layers.

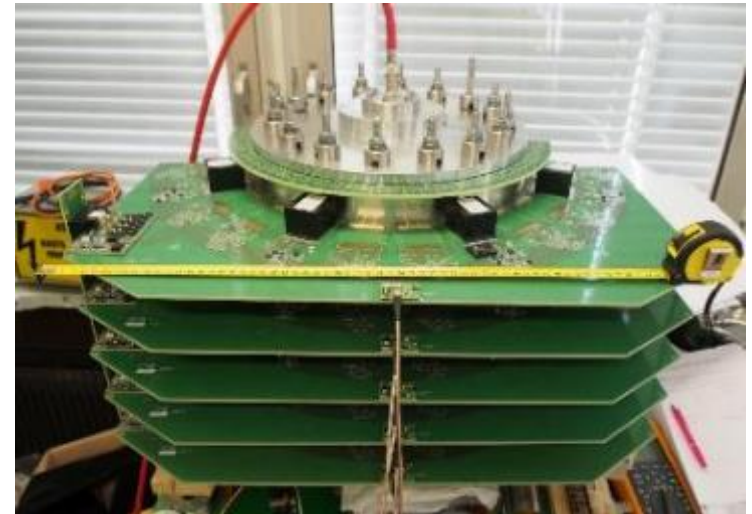


# Prototypes 4&5: Full-Scale, +/-12.5 kV, 20-layer, Inductive Adders for CLIC DR Extraction Kicker System

- Specifications according to requirements for CLIC DR extraction kicker:
  - Target waveform stability  $\pm 0.02\%$  for 900 ns at 12.5 kV
  - Target waveform repeatability  $\pm 0.01\%$  for 900 ns at 12.5 kV
- Status: under testing, measurements carried out with up to 19 constant voltage layers + 1 analogue modulation layer, up to 10.5 kV

Design Parameter	20-Layer Full-Scale Prototype	CLIC DR Extraction Kicker Modulator
Output Voltage (kV)	12.5	12.5
Output Current	309*	250
Voltage per layer	700	700
Number of layers	20	20
Pulse flat-top duration (ns)	1100	160 – 900
Pulse rise time [0.1-99.9 %] (ns)	100	< 1000
Pulse fall time [0.1-99.9 %] (ns)	100	< 1000
Flat-top stability (for 900* ns)	$\leq \pm 0.02\%$	$\pm 0.02\%$
Flat-top repeatability (for 900* ns)	$\leq \pm 0.01\%$	$\pm 0.01\%$

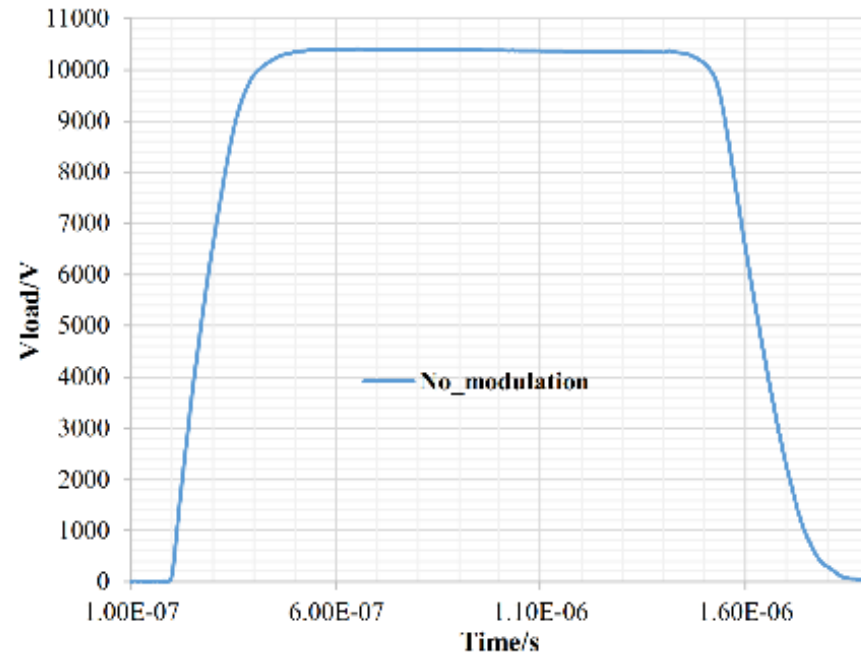
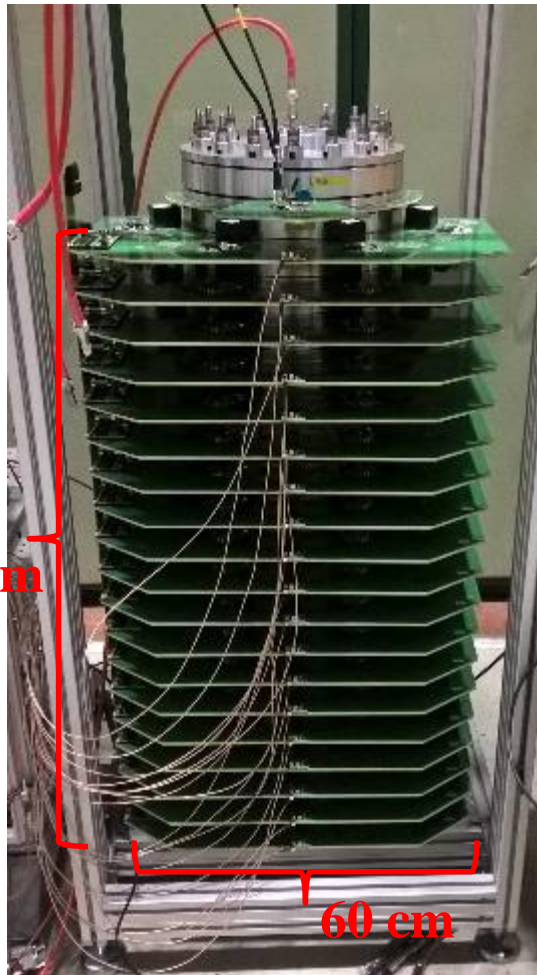
\*Stripline off-mode impedance  $40.5 \Omega$



First 5 layers of the 12.5 kV inductive adder assembled at CERN



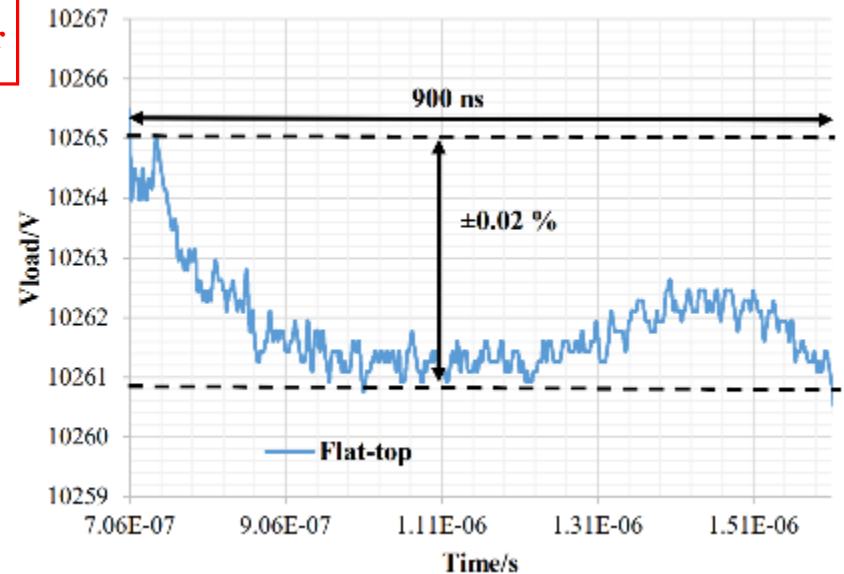
# Measurement without Modulation



- **Setup for the measurement:**
  - 20-layer prototype inductive adder
  - 18 constant voltage layers, with half-layer PCBs
  - 4 branches powered per layer, capacitors ( $48 \mu F/\text{layer}$ ) initially charged to 590 V.
  - **No modulation applied**
  - **Output voltage 10.4 kV, droop 60 V for 700 ns.**

⇒ Flat-top stability w/o compensation:  $\pm 0.3\%$  ( $\pm 30$  V) over 900 ns, at 10.4 kV

# Measurement on a Flat-top Pulse



## Setup for the measurement:

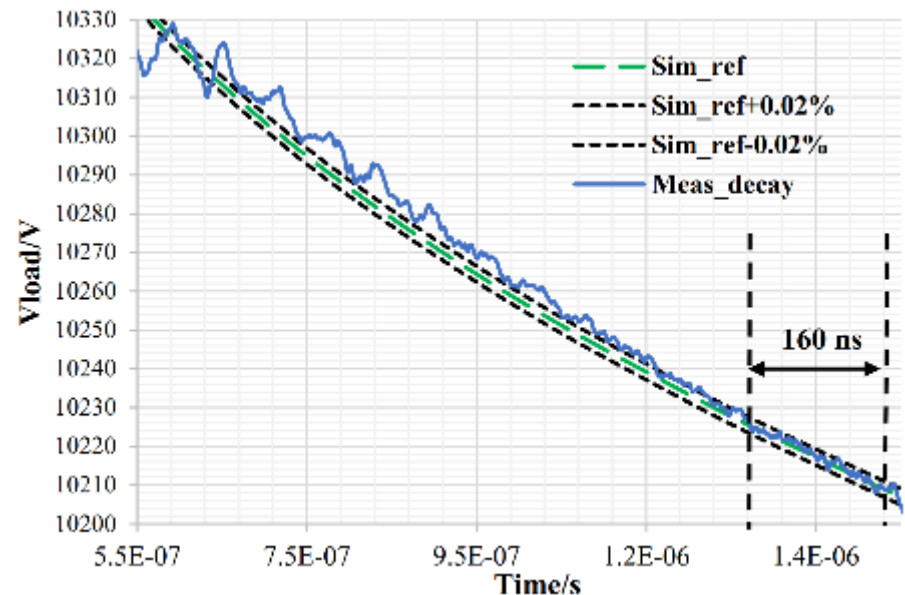
- 20-layer prototype inductive adder
- 19 constant voltage layers, with half-layer PCBs
- 4 branches powered per layer, capacitors (48  $\mu\text{F}/\text{layer}$ ) initially charged to 605 V.
- **1 active analogue modulation layer**
- **Active compensation of droop**
- **Output voltage  $\sim 10.3$  kV**

- ⇒ **Until recently, the specifications called a "flat-top" pulse.**
- ⇒ **Manually tuned compensation, not yet fully optimised: could be improved e.g. by applying frequency domain compensation, with Fast Fourier Transform analysis.**
- ⇒ **Flat-top stability:  $\pm 0.02\%$  ( $\pm 2.2$  V) over the 900 ns flat-top at 10.2 kV (for an average of 1k measured pulses).**

# Measurement on an Optimum Controlled Decay Waveform

## ■ Setup for the measurement:

- 20-layer prototype inductive adder
- 18 constant voltage layers, with half-layer PCBs
- 4 branches powered per layer, capacitors (48  $\mu\text{F}/\text{layer}$ ) initially charged to 605 V.
- **1 active analogue modulation layer**
- **Active modulation applied to adjust the flat-top to a controlled decay**
- **Output voltage  $\sim 10.3$  kV (decay)**




- ⇒ **Waveform stability  $\pm 0.02\%$  over 160 ns wrt. the optimum decay waveform (according to CLIC DR kicker stability requirement) at  $\sim 10.3$  kV (for an average of 100 waveforms)**
- ⇒ **Manually tuned compensation, not optimised: can be improved e.g. applying frequency domain compensation, with Fast Fourier Transform analysis.**
- ⇒ **Target for next measurements: stability  $\pm 0.02\%$  over the first and last 160 ns of a 900 ns (or over 900 ns) decay wrt. the optimum decay waveform.**

# Summary & Future Work


- Two full-scale, 20-layer, +/-12.5 kV CLIC DR extraction kicker inductive adders have been built at CERN and testing is on-going.
- Active analogue modulation methods applied to a) improve the flat-top stability of the waveforms and b) to adjust the output waveform for a controlled decay waveform.
- The best measured flat-top stabilities, with active droop compensation (not fully optimised) :
  - $\pm 0.02\%$  over 900 ns for a flat-top pulse at 10.3 kV.
  - $\pm 0.02\%$  over the best 320 ns for a decay waveform at 10.3 kV
- Next steps
  - Measurements at 12.5 kV (nominal voltage)
  - Decay waveform measurements with  $\pm 0.02\%$  stability over 900 ns.
  - Measurements with two inductive adders by measuring the difference of two pulses with opposite polarities, for stability and repeatability.
  - Design of automated control system for the waveform corrections.
  - Measurements of two 12.5 kV inductive adders with a prototype stripline kicker installed in a beamline at Alba Synchrotron Light Source in Spain (September 2018).
- Much interest for inductive adder technology at CERN, regarding e.g. FCC project and replacement of ageing systems in existing accelerators at CERN:

**see poster "Prototype Inductive Adder for the Proton Synchrotron at CERN" ID: 3P44 on Wednesday**



## Prototype Inductive Adder for the Proton Synchrotron at CERN

D. Wood, M.J. Barnes, J. Holma, E. Kramer  
CERN, Geneva, Switzerland



ID: 3P44 Session ID: 2966

**Abstract**

Several prototype inductive adders (IA), for use with kicker systems, each with very different specifications, are under construction at CERN. Historically pulse generators for kicker systems use thyratrons and either a Pulse Forming Network (PFN) or a Pulse Forming Line (PFL). The IA has several advantages compared to these conventional pulse generators, including: The use of semiconductor switches instead of thyratrons, the modularity, scalability and ease of including inductances, and the possibility to actively reduce the ripple to improve pulse quality. In addition, semiconductor technology that can both fabricate and assemble the PFN or PFL is no longer available in a capacitor bank. The IA is a very interesting option for older kicker systems, especially for those where space PFLs are no longer available. The kicker systems of the proton synchrotron (PS) at CERN were built in the 1970s and are hydrogen-based. Due to increased need for maintenance and difficulties to source various components, the replacement of the PS kicker pulse generators by a modern technology is a very attractive option. Hence studies have started to design and build a prototype IA for use in various kicker systems in the PS. Thanks to this modular design the design of a prototype IA developed for the Future Circular Collider (FCC) inductive adder can be readily modified to meet the required voltage and impedance values for the PS systems. In particular the IA is being considered for the PS kicker systems: the proton extraction kicker system (KFA and KFA11) and the proton injection kicker system (KFA4) with a pulse length of 2.1 and 2.5  $\mu$ s respectively. The paper gives a short introduction to IA technology, and discusses the challenges for an IA prototype to meet the PS pulse requirements.

### IA requirements of the PS kicker systems

System	KFA4	KFA11	KFA11	KFA4	
Purpose	inj.	ext.	inj.	ext.	
Magnet current	A	3042	2543	2697	2400
System impedance	$\Omega$	26.3	15.7	15	6.25
Magnet voltage	kV	40	40	40	15
Max. Flat-top length	$\mu$ s	2.6	2.1	2.1	2.0
Field rise time 5 % - 95 %	ns	30	37	63	430
Single way transit time	ns	33	76	96	355
Current rise time	ns	49	43	42	75
Termination	$\Omega$	S/C	15	15	6.25

\* Note 1: System requirements of the proton extraction and injection kicker systems of the PS. Values from [2] to [4].

### Inductive Adder principle

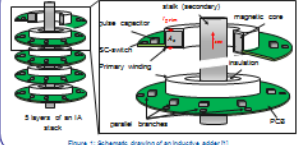


Figure 1: Schematic drawing of an inductive adder [1].

### Layer design for an Inductive Adder for the Proton Synchrotron at CERN

System requirements of all these systems also similarities

- Fast rise time
- High voltage of 40 kV
- Compatible current values (2.5 - 3.1 kA)
- Inductance system impedance (15 - 26  $\Omega$ )
- One prototype can fulfil most of the requirements of all systems
- Operation of an IA in serial circuit mode (KFA4) requires further investigation

Factors influencing the layer impedance

- Ratio of primary, inner diameter (D) and stack diameter (S)
- Inductance material between primary and secondary (Z)
- Layer height (h)
- Inductance of primary winding (L<sub>p</sub>)

Factors influencing the rise time:

- Layer height (h)
- Inductance material  $\mu$  and  $\epsilon$
- Primary inductance L<sub>p</sub>
- Insulation diameter ratio D/S
- Output voltage, layer voltage, number of layers (N)
- Switching time of switching device (SCM/IGBT)

$$L_p = N \left( \frac{\mu_0}{4\pi} \right) \left( \frac{D^2}{h} + \frac{S^2}{4h} \right) \approx N \frac{\mu_0 D^2}{4\pi h} \left( 1 + \frac{S^2}{4D^2} \right)$$

The layer height (h) and the number of layers are the most efficient factors to reduce the propagation delay and hence the rise time since other values are prescribed to match the impedance (Z).

### FCC Prototype

The prototype IA for the FCC injection system is currently under construction at CERN. The layer height of the prototype was reduced to obtain a shorter rise time (t<sub>r</sub>). A final prototype of 10 layers is built and has been tested up to 10 kV.

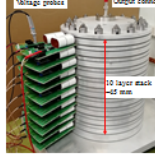
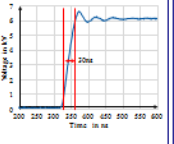



Figure 2: 10 layer IA prototype for the FCC injection system. Each layer is equipped with two parallel branches on one PCB.

Figure 4: Rising edge of the 10 layer prototype output pulse. A rise time (1 % - 95 %) of 320 ns was measured.

### CONCLUSIONS

Voltage per layer	kV	1.2
Min. No. of layers		24
No. of branches		24
Current per branch	A	130
Primary inductance	nH	24
Capacitance per layer	pF	340
Outer insulation diameter	mm	105
Inner insulation diameter	mm	85-95
Min. Core-section area of mag. Core	cm <sup>2</sup>	10.8

\* Note 2: Parameters for a prototype inductive adder for the PS systems.

Parameters for a prototype IA for several PS kicker systems have been considered. The rise design is based on that of the prototype IA for the FCC injection, which is designed for fast rise times but at significantly lower voltage. First measurements on the 10 layer prototype for the FCC injection seem very promising. However, the 40 kV output pulse required for the CERN PS kicker results in a relatively high stack with an unacceptably long two-way propagation delay. Hence, to reduce the two-way propagation delay of the IA stack to an acceptable level, the height of the stack must be significantly reduced - which will require the number of layers and height of individual layers to be reduced. This means IGBTs and pulse capacitors with significantly increased voltage rating, and magnetic cores with reduced height. i.e. increased core diameter and available flux density. IGBTs/IGBTs with a faster switching time at turn-on, are also highly desirable.

**References**

[1] D. Wood, M.J. Barnes, J. Holma, E. Kramer, "Prototype Inductive Adder for the Proton Synchrotron at CERN", *IPAC2018*, pp. 1038-1041, 2018.

[2] D. Wood, M.J. Barnes, J. Holma, E. Kramer, "Prototype Inductive Adder for the Proton Synchrotron at CERN", *IPAC2018*, pp. 1038-1041, 2018.

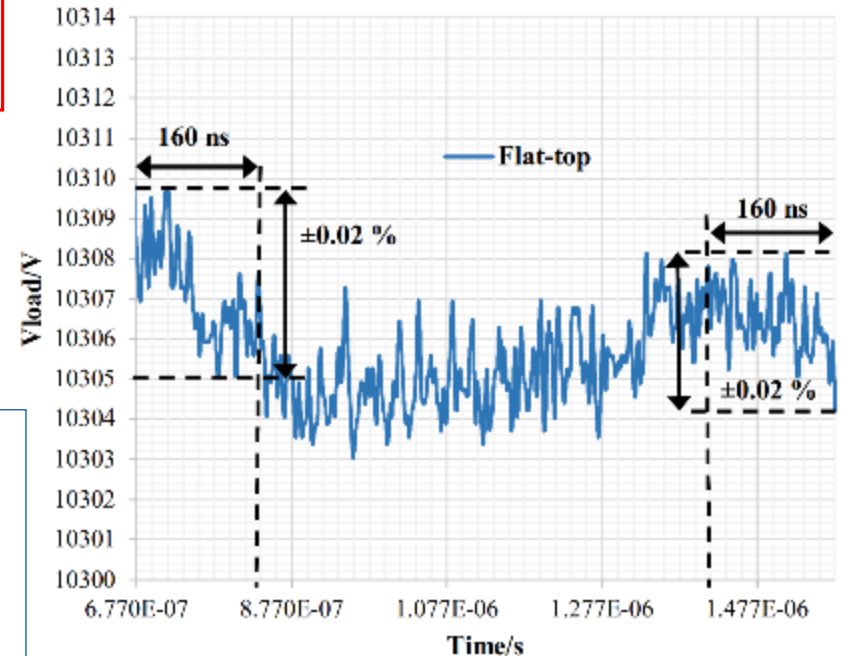
[3] D. Wood, M.J. Barnes, J. Holma, E. Kramer, "Prototype Inductive Adder for the Proton Synchrotron at CERN", *IPAC2018*, pp. 1038-1041, 2018.

[4] D. Wood, M.J. Barnes, J. Holma, E. Kramer, "Prototype Inductive Adder for the Proton Synchrotron at CERN", *IPAC2018*, pp. 1038-1041, 2018.





# Prototype 4&5: Flat-top Pulse, with Modulation



## Setup for the measurement:

- 20-layer prototype inductive adder
- 19 constant voltage layers, with half-layer PCBs
- 4 branches powered per layer, capacitors (48  $\mu\text{F}/\text{layer}$ ) initially charged to 605 V.
- **1 active analogue modulation layer**
- **Active compensation of droop**
- **Output voltage 10.3 kV**

- ⇒ **Until recently, the specifications called a "flat-top" pulse.**
- ⇒ **Manually tuned compensation, not yet fully optimised: could be improved e.g. by applying frequency domain compensation, with Fast Fourier Transform analysis.**
- ⇒ **Flat-top stability:  $\pm 0.02\%$  ( $\pm 2.3\text{ V}$ ) over the first and last 160 ns of the 900 ns flat-top and  $\pm 0.03\%$  ( $\pm 3.3\text{ V}$ ) over 900 ns, at 10.2 kV (for an average of 100 measured pulses).**