# Inductive Adders for the DR Extraction Kickers

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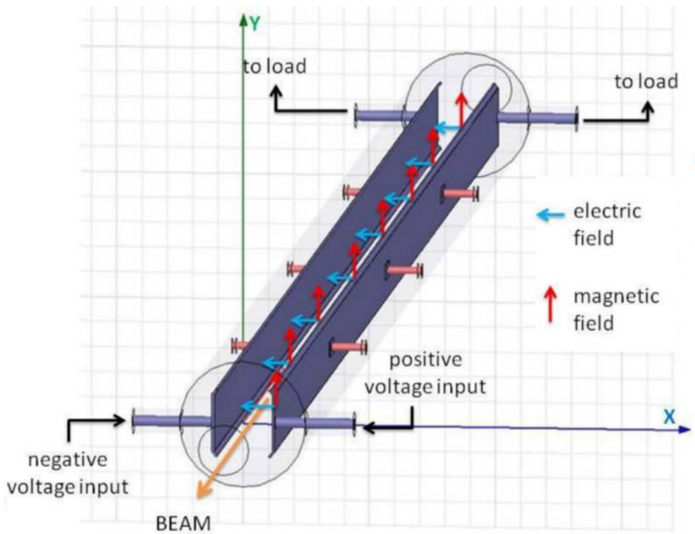
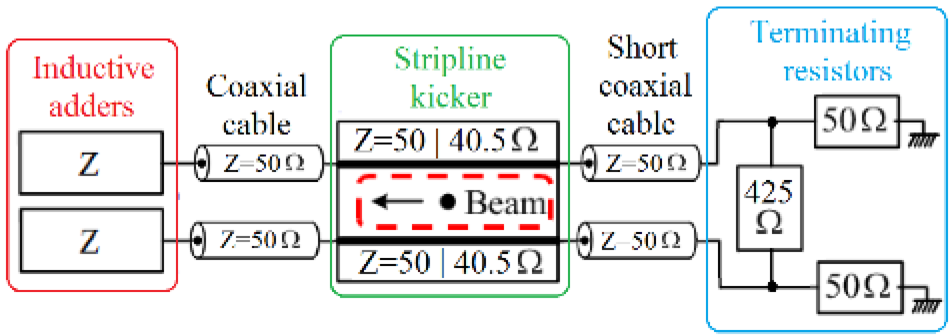
# Outline

- Specifications for CLIC DR Extraction Kickers
- Inductive Adder
  - Schematic and features
  - Active analogue modulation
- Measurements on Prototype Inductive Adders
  - Without modulation
  - Flat-top pulse
  - Controlled decay waveform
- Summary & Future Work

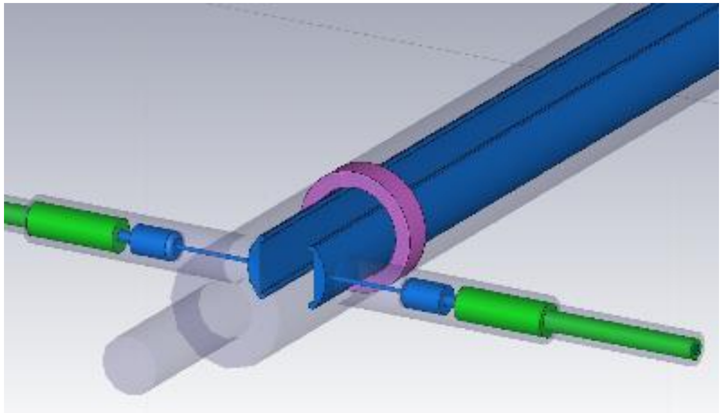
# CLIC DR Extraction Kicker System

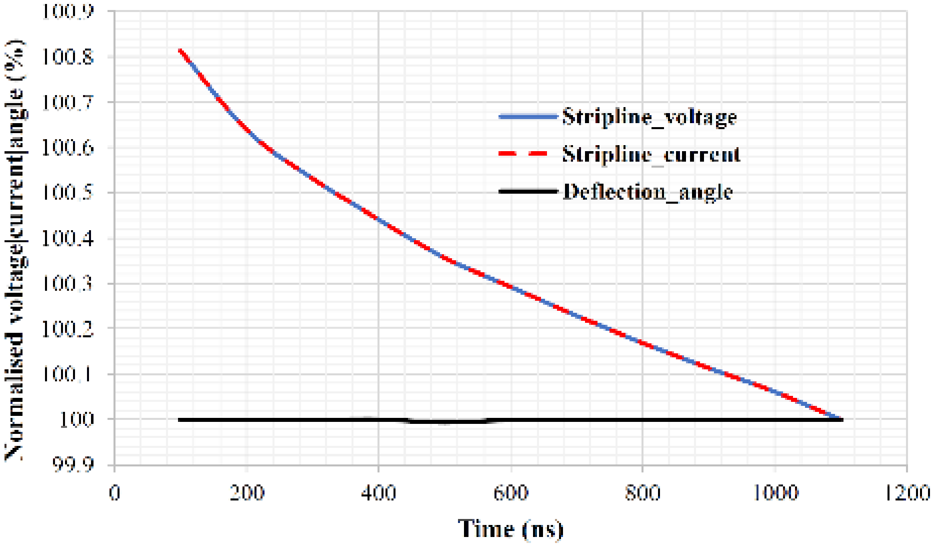



- Stripline kicker (left): both electric and magnetic fields deflect the beam.
- Two modulators, i.e. inductive adders, needed to generate positive and negative pulses for stripline electrodes
- Impedance of each electrode is 50 *Ω* when "off" (even mode) and 40.5 *Ω* when "on" (odd mode): both modes are matched with a terminating resistor network.

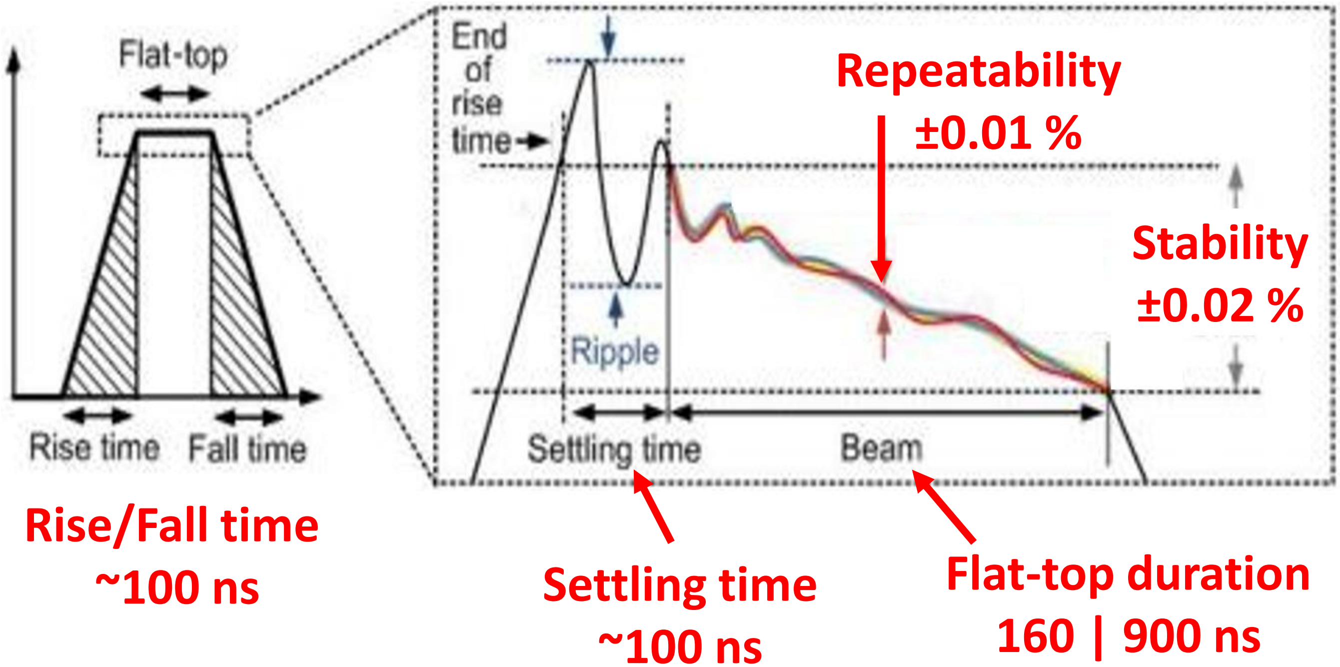
# Reference Waveform for the CLIC DR Inductive Adders: ”Controlled Decay”






- The impedance of the stripline kicker is not constant during a pulse: in order to keep the total deflecting electric and magnetic field stable the voltage and current need to be modulated.
- A ”controlled decay waveform” (right), given by simulations (C. Belver-Aguilar), gives ±0.02 % flat-top stability for the total deflecting field.

# Specifications for the CLIC DR Extraction Kicker Pulse




Voltage: ±12.5 kV
Current: 309 A (~40.5 Ω load)
Stability: ±0.02 % wrt. a simulated, optimum, reference decay waveform
Repeatability: ±0.01 %
Repetition rate: 50 Hz

# 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

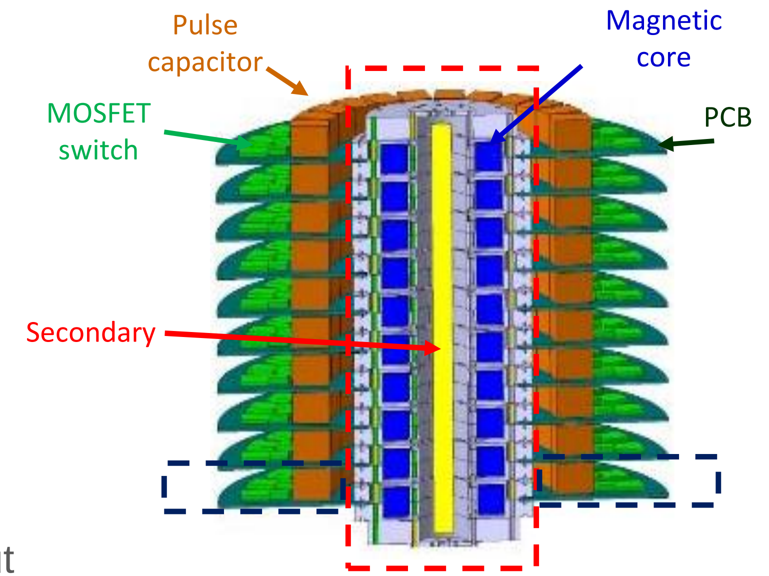
+ The output voltage can be modulated during the pulse by passive/active analogue modulation.

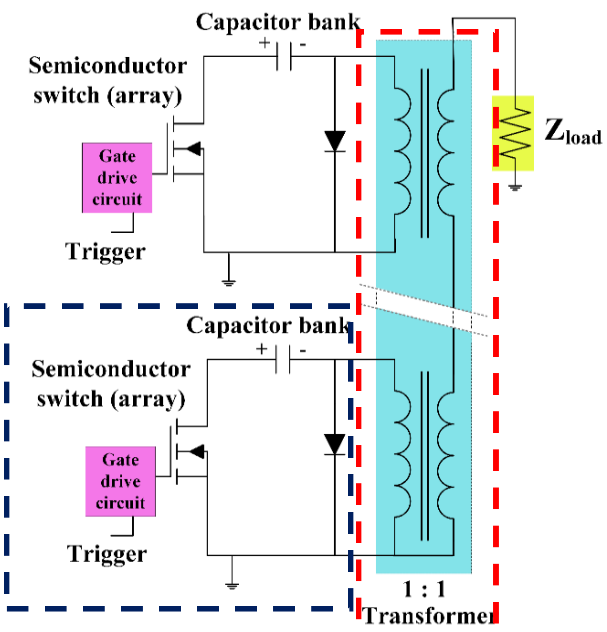
+ Possibility to generate positive or negative output pulses with the same adder: the polarity of the ouput pulses can be easily changed by grounding the other end of the output of the adder

+ All control electronics referenced to ground potential.

+ Built-in fault tolerance 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).

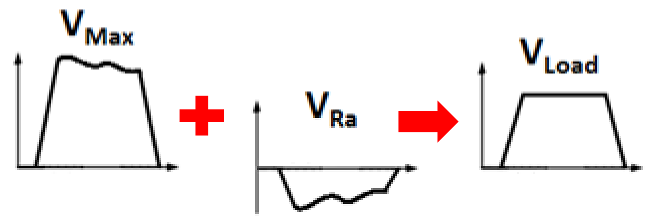
+ Modularity: the same design can potentially be used for CLIC DR & PDR kicker modulators and combined extraction + dump kicker (12.5/17.5 kV)

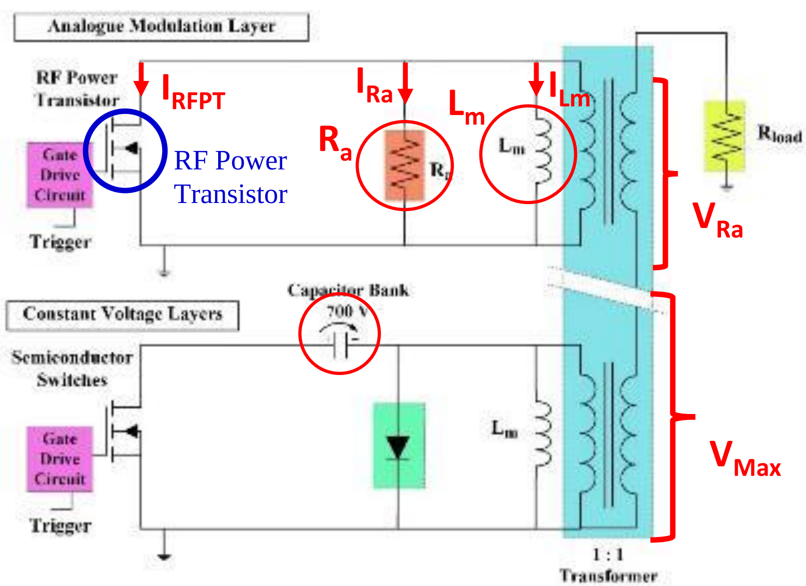


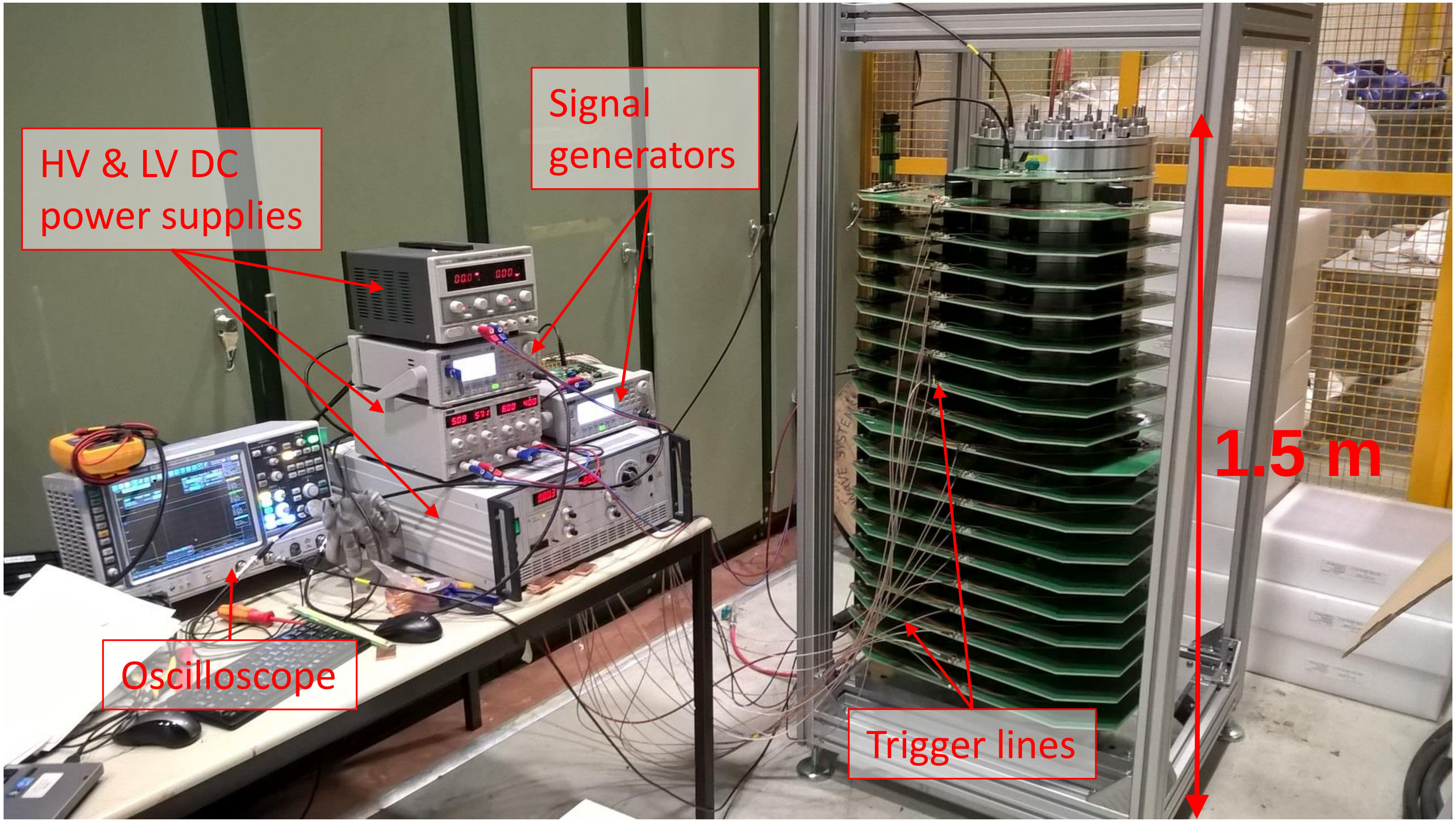
# Active Analogue Modulation

- 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.

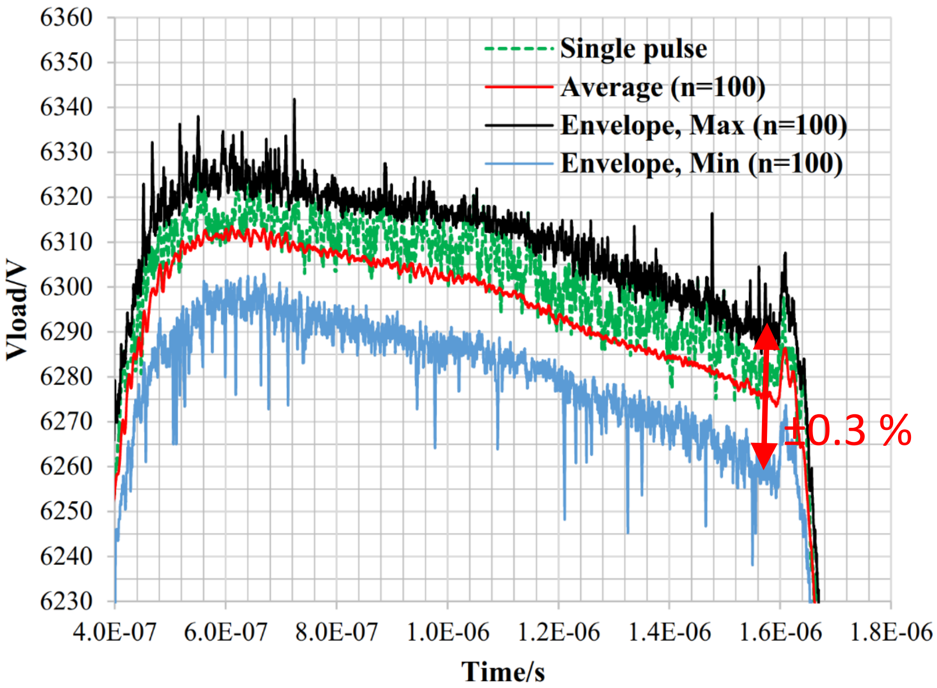


# Prototype 4: 20-layer, ”Full-scale”, Inductive Adder for CLIC DR Extraction Kicker



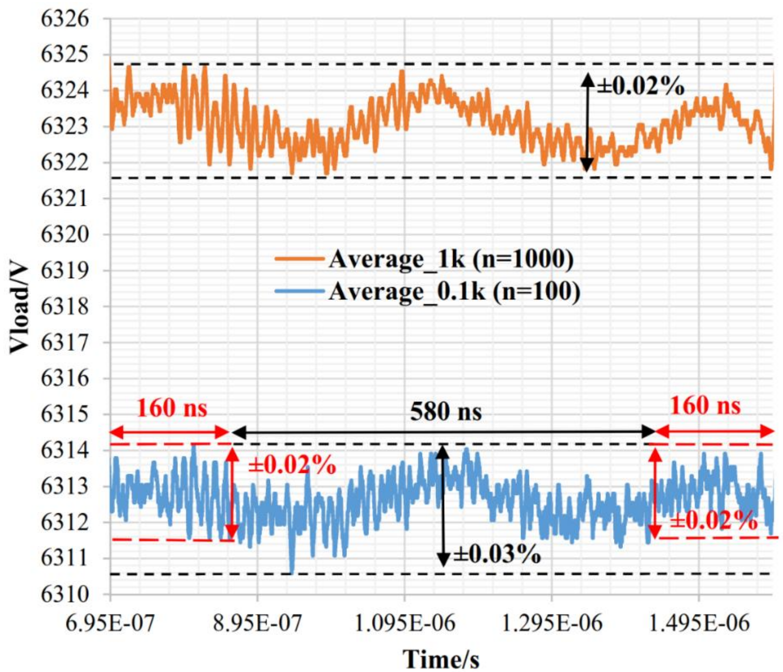
# Measurement without Modulation

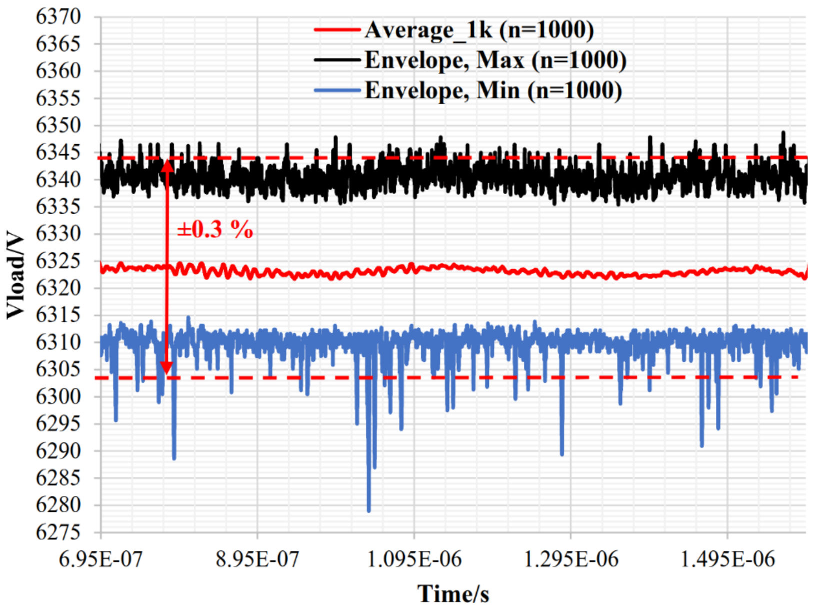



- Setup: 17 constant voltage layers
- Initial capacitor voltage 386 V/layer
- Load voltage: 6.3 kV
- Load current: 125 A (50 Ω load)
- Stability: ±0.3 % over 900 ns (wrt an ideal flat-top pulse)
- Min/max envelopes (repeatability): ±0.3 %

- Averaging (n=100) applied to improve resolution of the oscillscope (Without modulation up to 14 bits, at 100 MHz)
- It was found that min/max envelopes were defined by sensitivity settings of the ”16-bit” high-end R&S oscilloscope: approximately ±0.2 % of the full channel range.

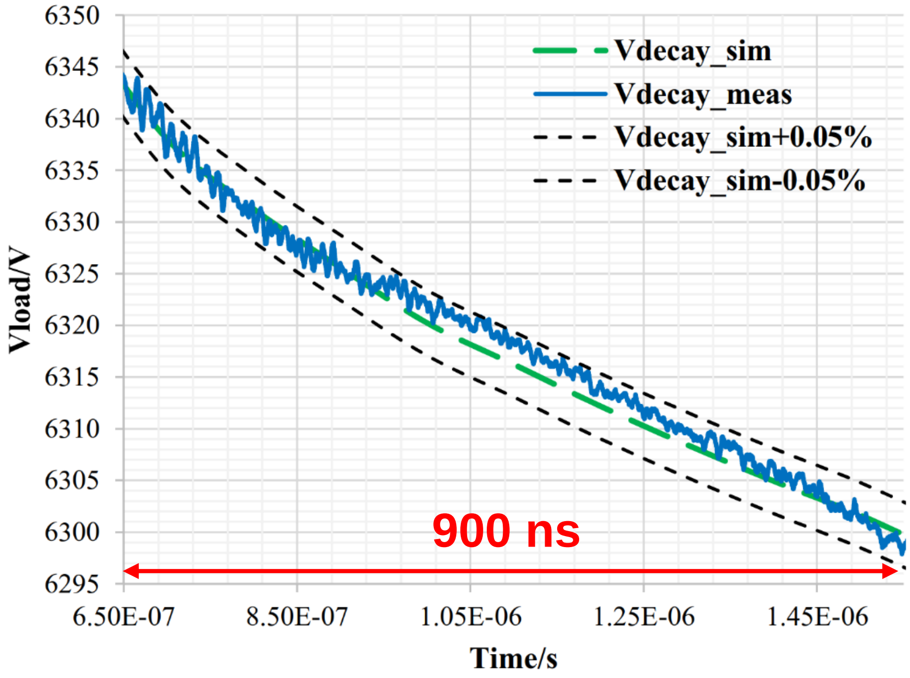
# Measurement on a Flat-top Pulse



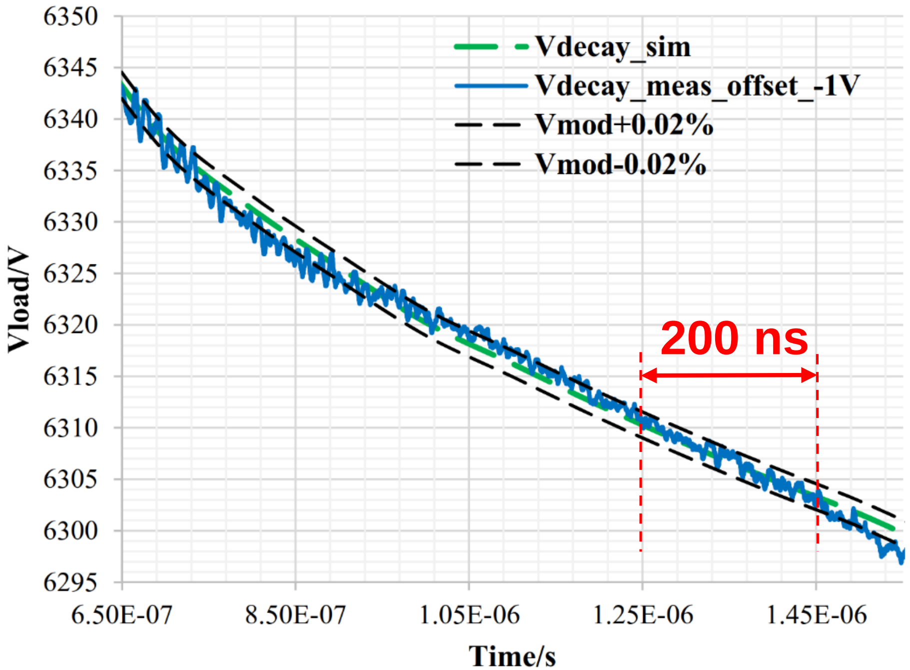

- Setup: 17+1 layers, active analogue modulation for a flat-top pulse
- Initial capacitor voltage 400 V/layer
- **Flat-top stability ±0.02 % (±1.55 V) at 6.3 kV over 900 ns**, at a half of the nominal voltage (for average of 1000 pulses).
- Flat-top stability ±0.02 % (±1.5 V) at 6.3 kV over the first and last 160 ns, of 900 ns, for average of 100 pulses (lower resolution)
- Min/max envelopes ±0.3 %: not changed when modulation applied!

# Measurements on a Decay Waveform




- Setup: 17 constant voltage layers +1 active analogue modulation layer
- Initial capacitor voltage 400 V/layer
- Load voltage: 6.3 kV
- Load current: 125 A (50 Ω load)
- **Stability: ±0.05 % over 900 ns (wrt an optimum decay waveform)**

# Measurements on a Decay Waveform



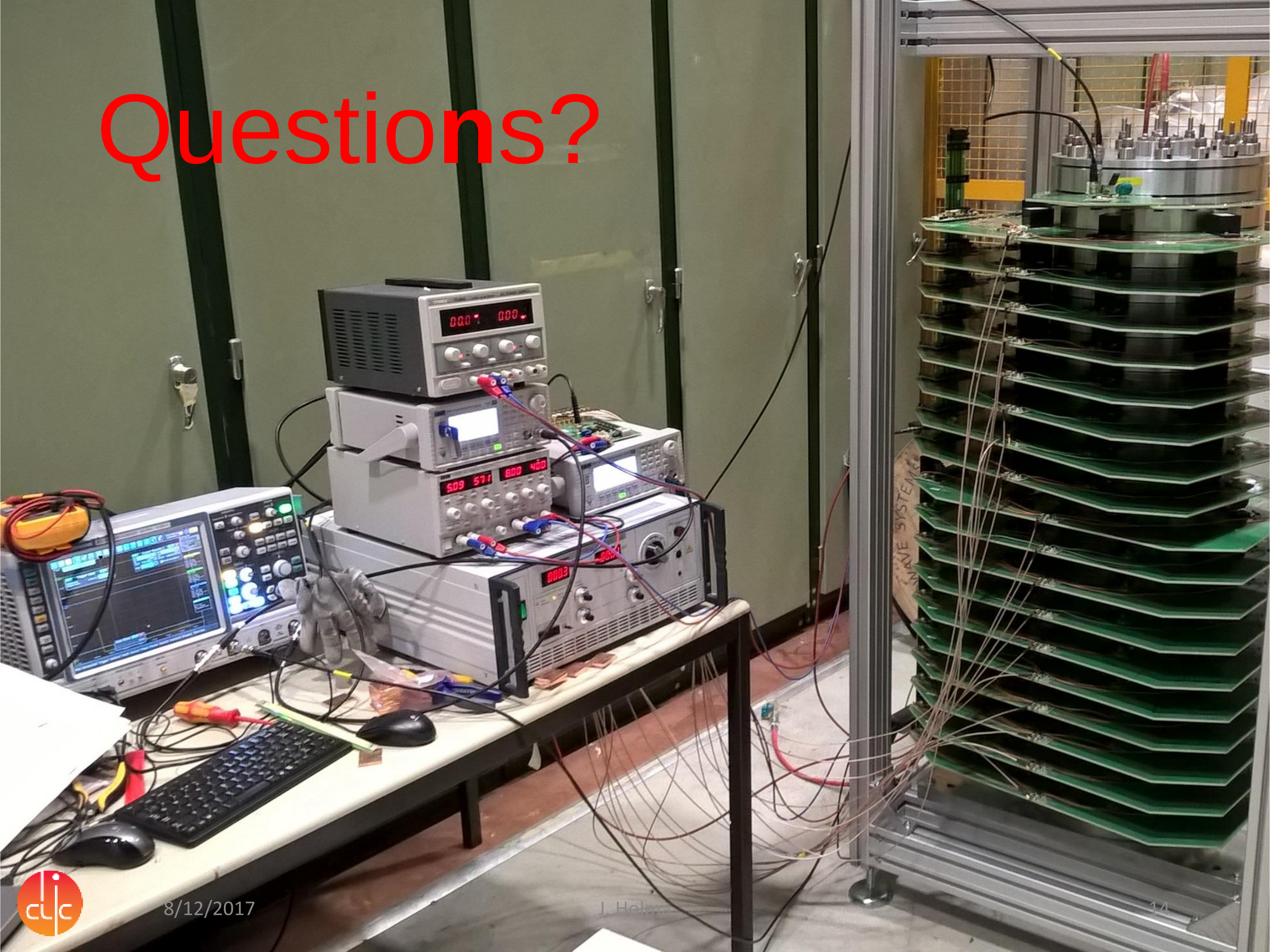

- Setup: 17 constant voltage layers +1 active analogue modulation layer
- Initial capacitor voltage 400 V/layer
- Load voltage: 6.3 kV
- Offset: -1 V (mathematically applied)
- Load current: 125 A (50 Ω load)
- Stability: ±0.02 % over 200 ns (wrt an optimum decay waveform)

- **Flat-top stability ±0.02 % at 6.3 kV over 160 ns** (CLIC DR 1 GHz Baseline), at a half of the nominal voltage.
- Flat-top stability ±0.05 % at 6.3 kV over 900 ns (CLIC DR 2 GHz), at a half of the nominal voltage.

# Summary and Future Work

- **The specifications for the pulse power modulators for the CLIC DR kicker systems are very probably feasible.**
- The best measured flat-top/waveform stabilities with 1st full-scale prototype:
  ±0.02 % over 900 ns for a flat-top pulse at 6.3 kV
  ±0.02 % over 160 ns for a “controlled decay waveform” at 6.3 kV.
- Next steps
  - Measurements at nominal voltage 12.5 kV, with waveform stability to ±0.02 % over 900 ns.
  - Assembly of the 2nd full-scale, 20/28-layer, prototype: combined 12.5 kV/17.5 kV extraction kicker + dump kicker modulator.
  - Design of LabVIEW-based automated waveform correction control system
  - Measurements with different measurement techniques, to evaluate stability and repeatability of a single pulse: e.g. balanced measurement setup (from PSI, Switzerland) and pulse cancelling method (2nd 20-layer inductive adder needed)
- Future measurements of two 12.5 kV inductive adders with a stripline kicker installed in a beamline in an accelerator test facility (e.g. at Alba in Spain, in 2018).
- Much interest for inductive adder technology at CERN, regarding e.g. FCC and PS KFA kicker systems.

# Questions?



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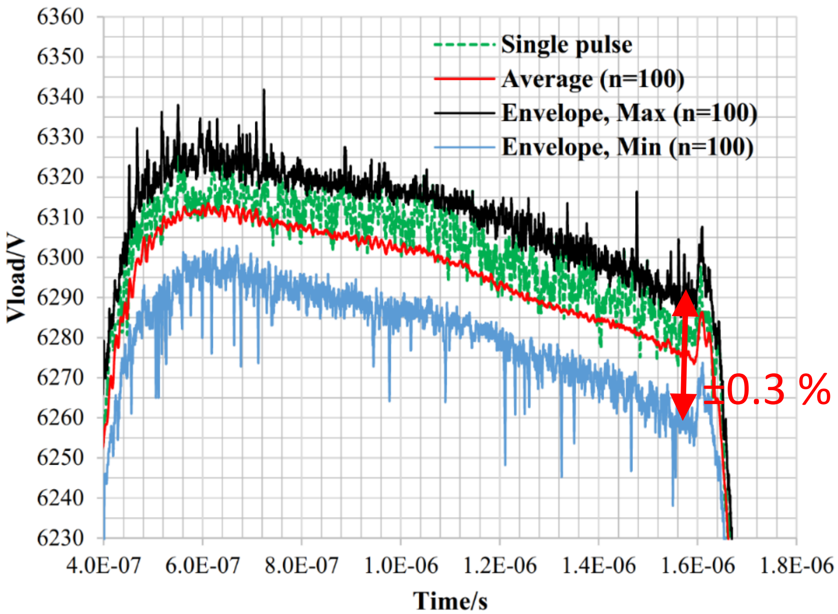
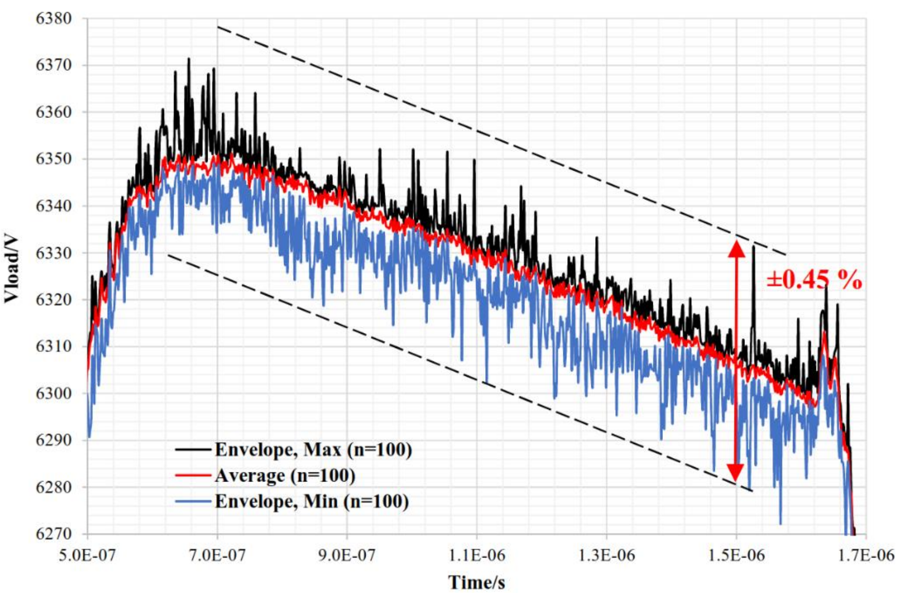
# Spare Slides

# Repeatability Measurements



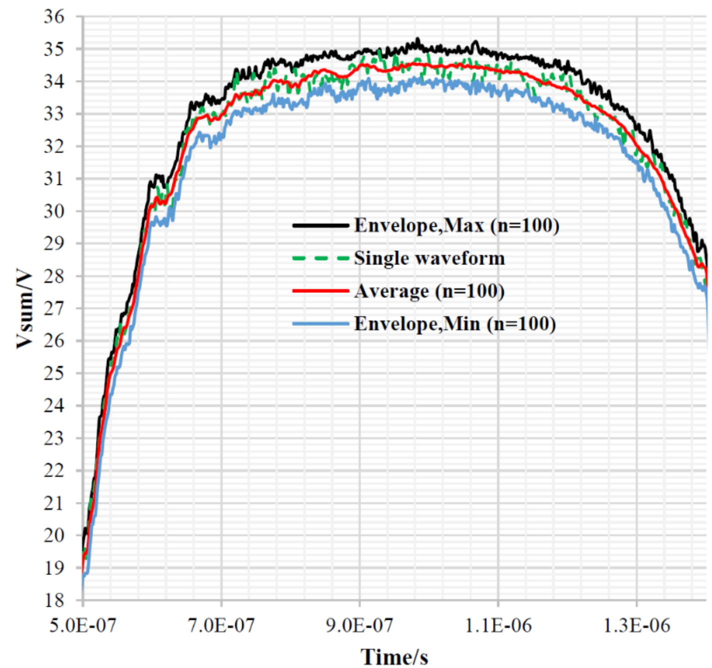

Rohde & Schwarz Rohde & Schwarz RTO1004 (16-bit at high resolution mode), sampling rate 10 GS/s (Δt=0.1 ns)




Tektronix MSO54 oscillscope (true 12-bit ADC), sampling rate 625 MS/s ((Δt=1.6 ns)

# Pulse Cancelling & Balanced Measurements

**A single current transformer to measure 2 pulses, with opposite polarities.**




Principle of pulse cancelling measurements: the difference of two pulses is measured, e.g. a flat-top and a decay waveform. Advantage: improved resolution (smaller dynamic range)

Principle of balanced measurements: a differential amplifier with a stable DC current source for a reference and fast clamping circuit to filter input signal when it is out of dynamic range.