Marx prototype pulse generator design and initial results

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Outline

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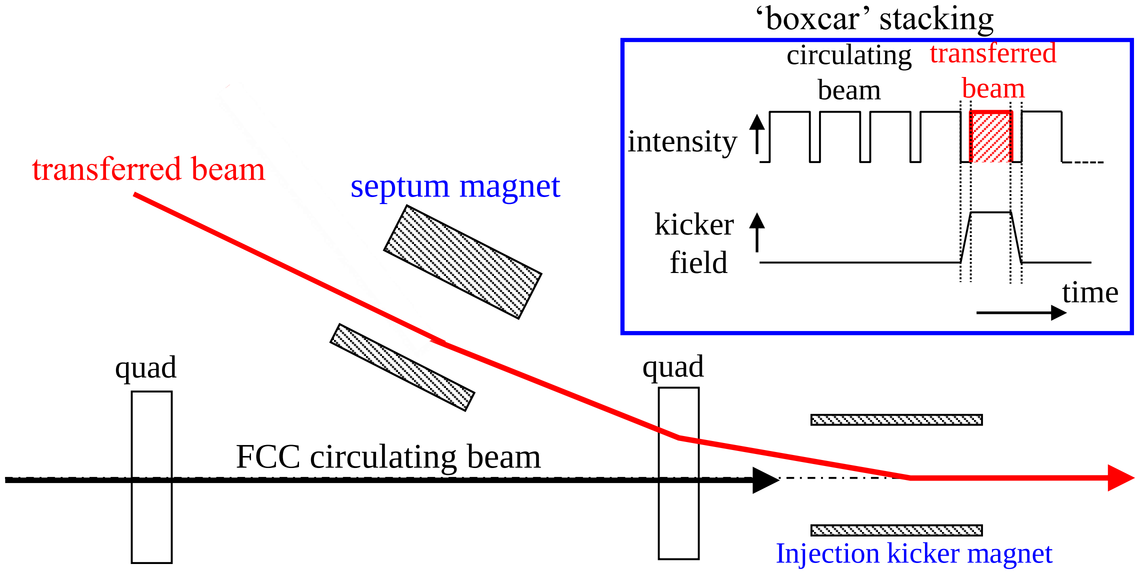
Parameters of injection system

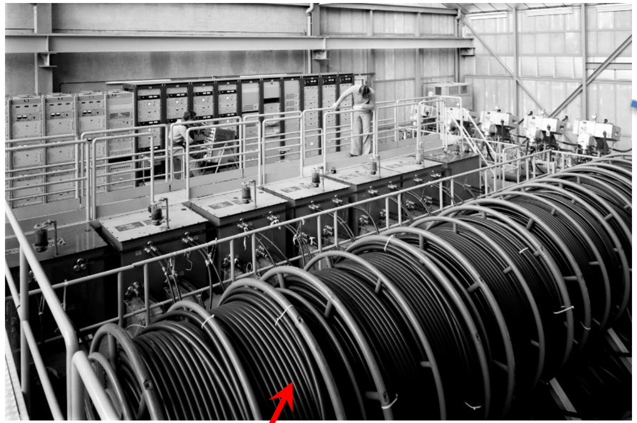
Hardware parameter	Unit	Kicker
Deflection	mrad	0.18
Integrated field	T·m	2.0
Field rise time	µs	0.43
Magnet single way delay	µs	0.355
System impedance	Ω	6.25
Magnet current	**kA**	**2.4**
Generator pulse rise time	**ns**	**75**
Generator output voltage	kV	15
Flattop length	µs	2.0
Flattop stability	%	±0.5



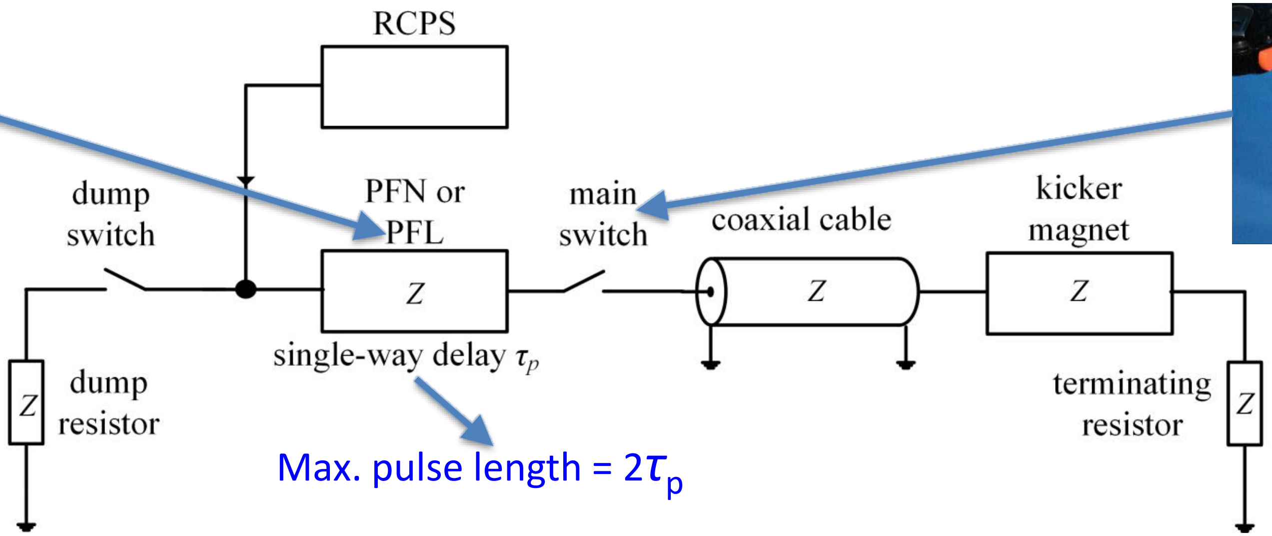
- Injection kicker system must be highly reliable;
- The baseline injection energy for the FCC-hh is 3.3 TeV;
- For machine protection reasons, a maximum of 80-100 bunches can be accepted by the injection protection system and hence safely transferred into FCC at a time;
- Each ring will be filled with 130 batches of **80** bunches (separated by 25 ns) ⇨ **2 µs** pulse.

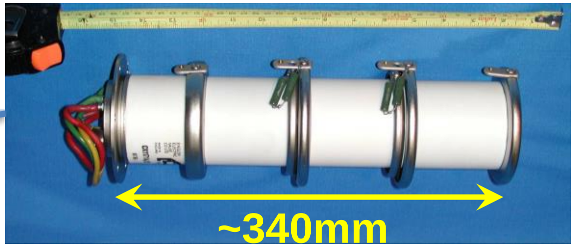
Oral presentation: FCC-hh transfer line and injection design, E. Renner, 11/04/2018, 15:30hrs.

Pulse power generators for kicker magnets



Reels of PFL





- Many kicker systems today use **thyratron** (gas tube) switches and pulse forming networks/lines (PFNs/PFLs);
  - **Long-term availability of thyratrons is a real concern**;
  - Thyratrons can exhibit unwanted, spontaneous, turn-on;
  - Thyratrons require a PFN/PFL: the **long-term availability of high-voltage PFL technology is a concern**.
- **Solid-state technology** and topologies show great promise for kicker application e.g.:
  - **Inductive Adder** (Oral presentation: “Inductive adder prototype pulse generator for FCC-hh kickers”, D. Woog, 11/04/2018, 11:10hrs);
  - **Marx Generator**.

Goal: to achieve reliable, fast-switch technologies based on semiconductor devices. **Both the Inductive Adder (<3us pulse width) and Marx Generator technologies are being actively pursued.**

Motivation & challenges

Semiconductor switches, such as SiC MOSFETs (metal-oxide-semiconductor field-effect transistors), can potentially be used in fast high current pulsed power accelerator applications to replace thyratrons and PFLs.

Thyratrons

- \+ Generally reliable
- \+ Robust (fault tolerant)
- \+ Relatively high voltage
- \+ Relatively high current
- – Long term availability
- – Spontaneous turn on
- – Can only be turned on

Versus:

MOSFETs

- \+ Cost-effective
- \+ Easy to use
- \+ Off-the-shelf
- \+ Flexible
- \+ Modular
- \+ Maintainability
- \+ **Can be turned on and off (thus PFL/PFN is not required)**
- – Relatively low voltage
- – Relatively low current

But…. Semiconductors have limited voltage and current rating. Hence, requires **series and parallel connection of power semiconductors** to achieve high pulsed power.

Solid-state Marx generator (1)

Electrical circuit first described by Erwin Otto Marx in 1924 – until recently the Marx did not use semiconductor switches.

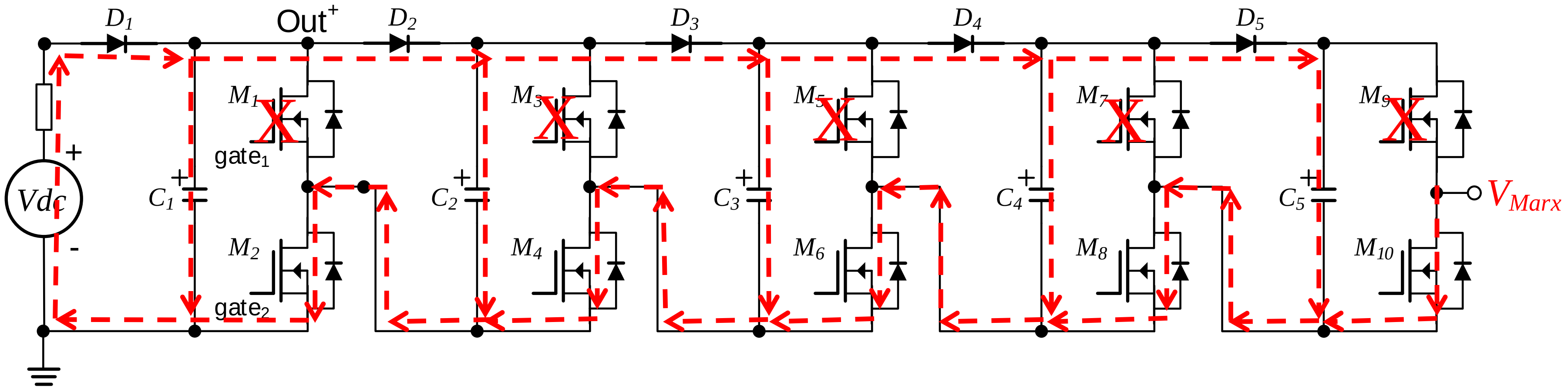
Concept: generate a high-voltage pulse from a low-voltage DC supply and components.

The circuit operates by (1) charging capacitors in parallel, then subsequently connecting them in series to generate a high-voltage output pulse.

STEP 1

1a) All the odd numbered MOSFETs/IGBTs (i.e. M_1, M_3, M_5, …) are off.

1b) The capacitors (C_1, C_2 , … C_5) are charged in parallel, from *Vdc*, by turning-on all the even numbered MOSFETs/IGBTs (i.e. M_2, M_4, M_6, …) [$V_{Marx} \approx 0$ V]:



Solid-state Marx generator (2)

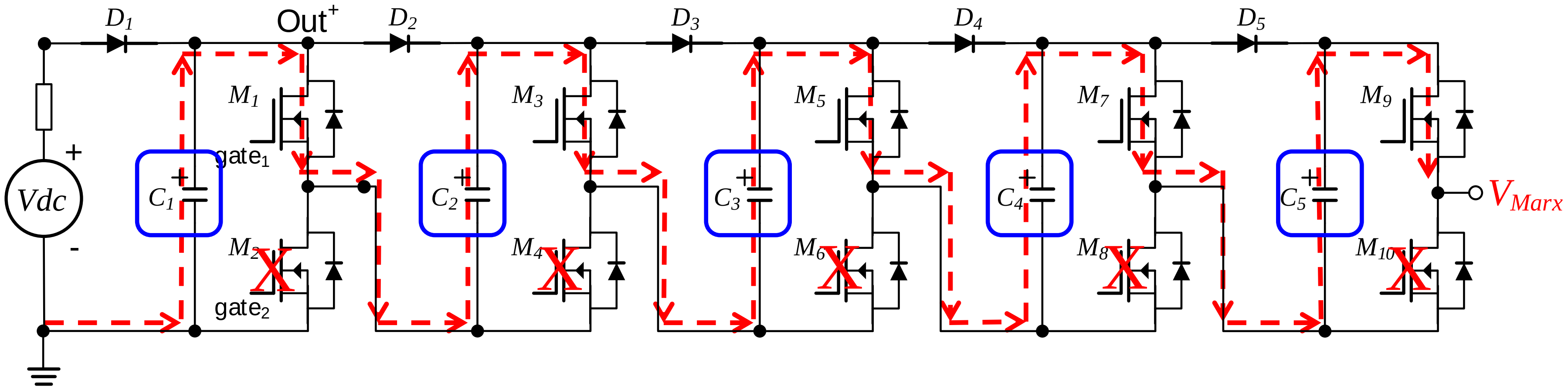
The circuit operates by charging capacitors in parallel, then (2) subsequently connecting them in series to generate a high-voltage output pulse.

STEP 2

2a) Capacitors C_1, C_2 , … C_5 have been charged to V_{dc} in step (1b). All the even numbered MOSFETs/IGBTs (i.e. M_2, M_4, M_6, , …) are then turned off.

2b) All the odd numbered MOSFETs/IGBTs (i.e. M_1, M_3, M_5, …) are then turned on, to connect the capacitors in series.

Here: $V_{\mathrm{MARX}} \approx 5 \cdot V_{\mathrm{dc}}$



For fast, rectangular, pulses MOSFET technology is required.

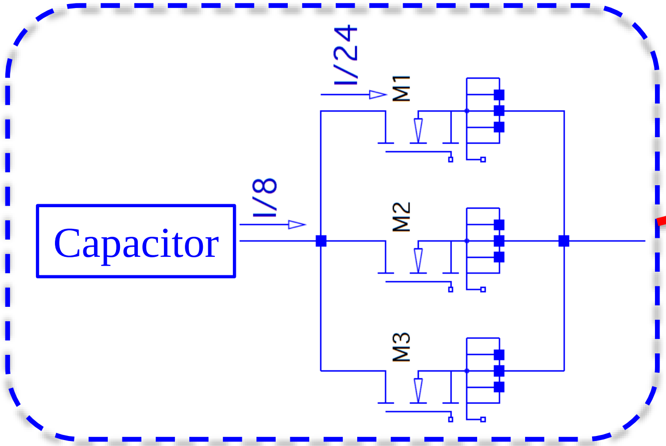
Marx generator solid-state modular concept

One MOSFET tested to date: CREE SiC MOSFET C3M0065090J, 900V, SiC MOSFET, in D2PAK-7L package, with separate emitter for gate voltage (C3M0065100J, 1000V, now available)

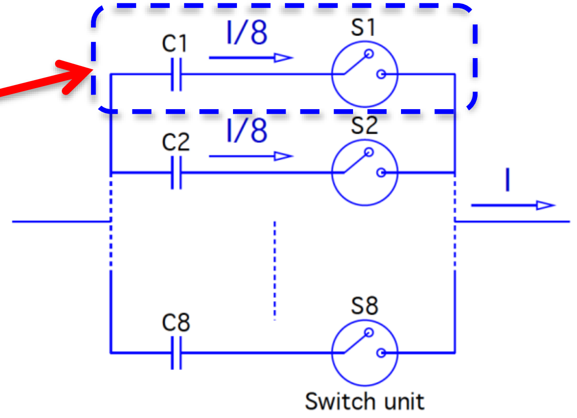
C3M0065090J data sheet parameter	Value
Min. Drain-Source Breakdown Voltage	900 V
Pulsed current	90 A
On-State Resistance	65 mΩ
Rise time (90 - 10 %)	9 ns
Fall time (10 - 90 %)	7.5 ns

- Each switch unit consists of a pulse capacitor and 3 SiC MOSFETs in parallel
- *n* staked (series) stages. Each stage consists of 8 switch units

Each switch unit (3 MOSFETs):

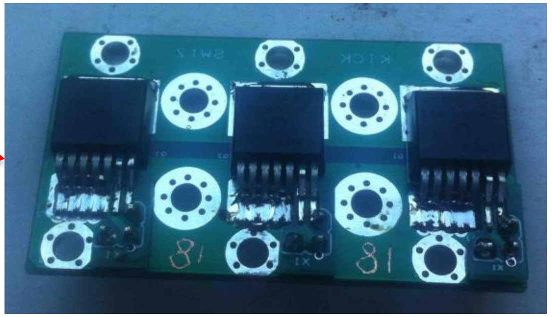


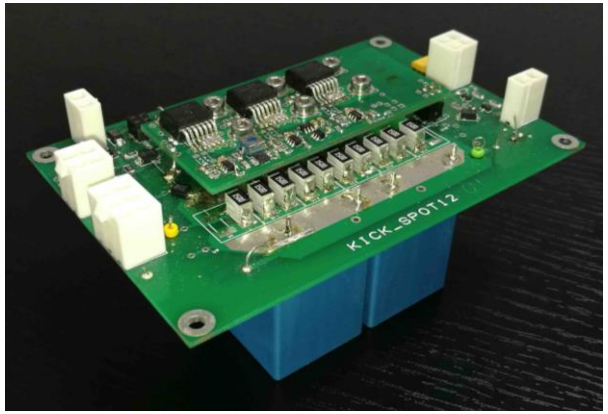
Each Marx stage (8 switch units):



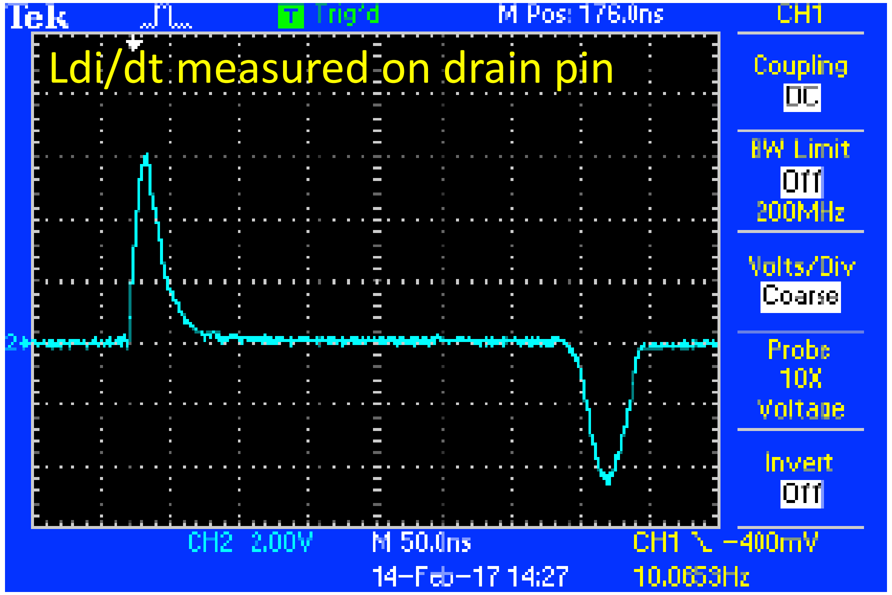
Marx MOSFET switch unit: measurements

Switch unit: 3 parallel MOSFETs with a 60μF capacitor:



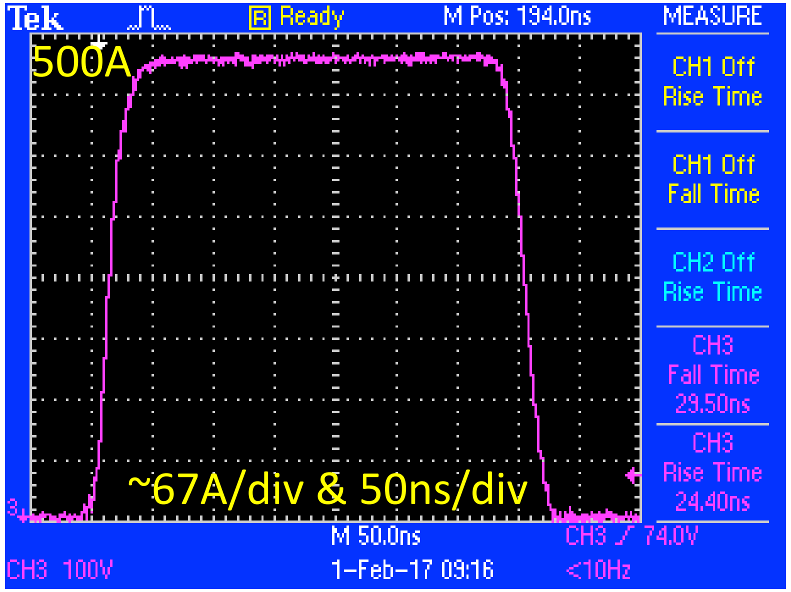


Switch unit: current sharing of 3 parallel MOSFETs:



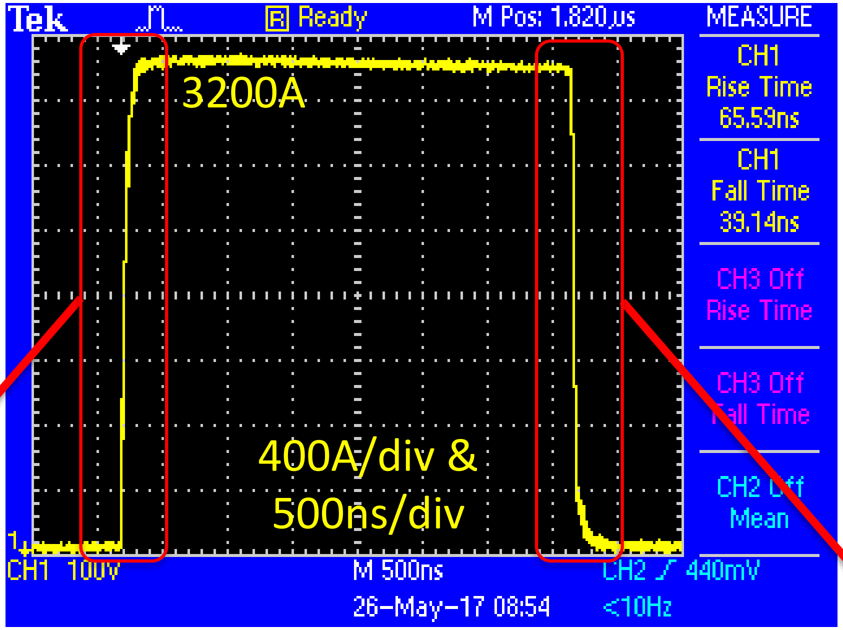
M1	166 A (33%)
M2	152 A (31%)
M3	182 A (36%)

750 V pulse across 1.5Ω (500 A)



One MOSFET Marx stage: measurements

Operating conditions: *U*dc=800V, *R*load=0.25Ω ⇨ ~3200 A expected:

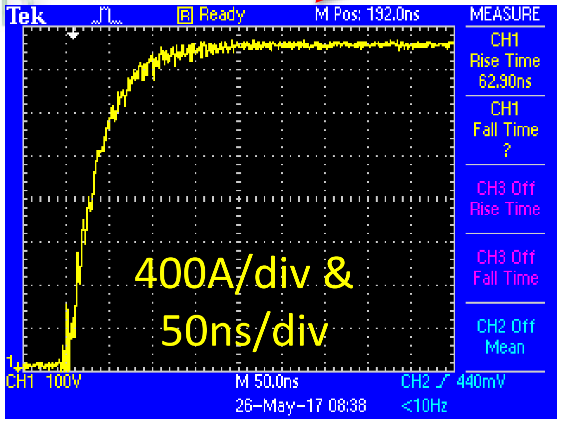


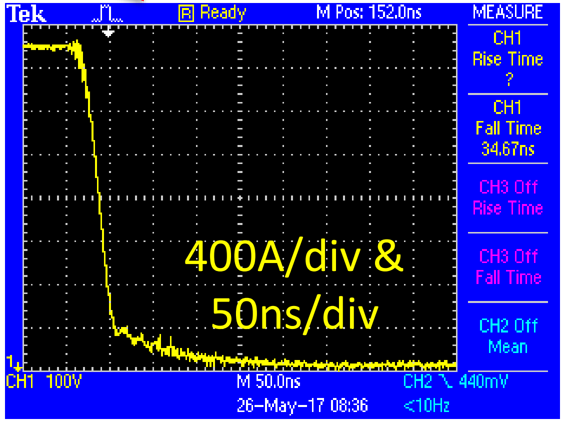
Voltage "drop": 40V

Voltage droop: 10V (~1.3%)

Rise time:
65ns (10-90%)

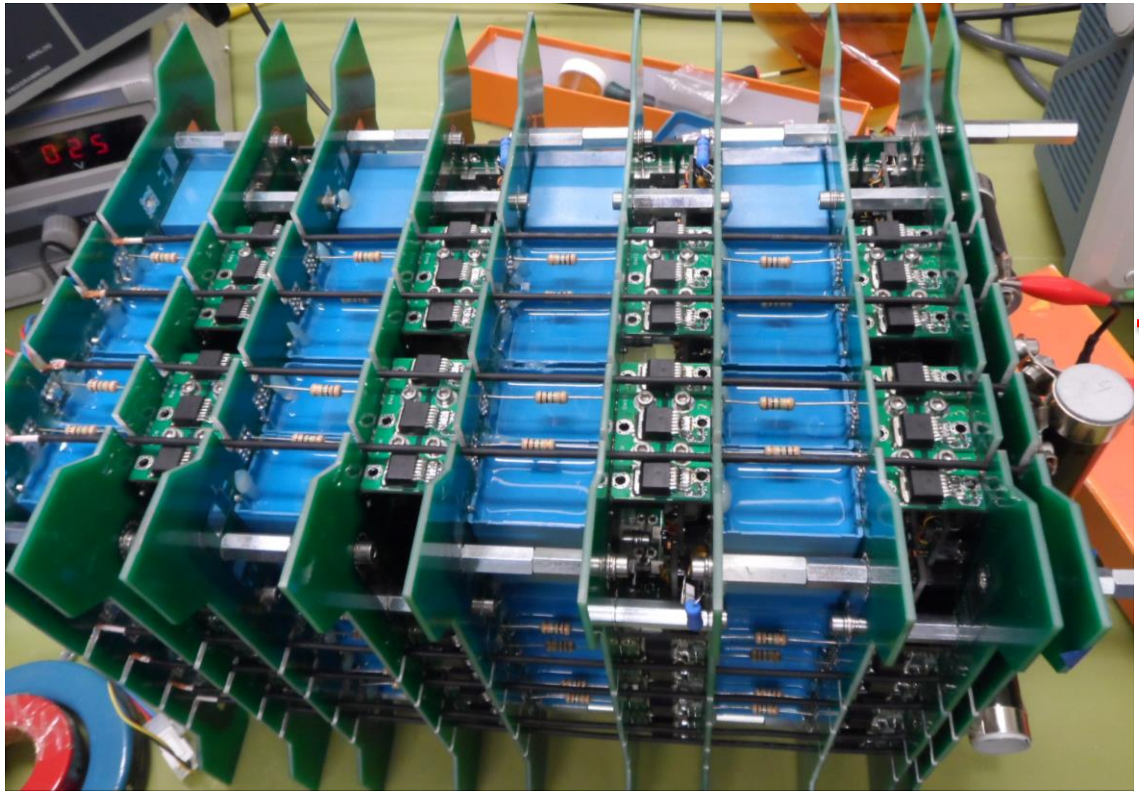
Fall time:
39ns (90-10%)



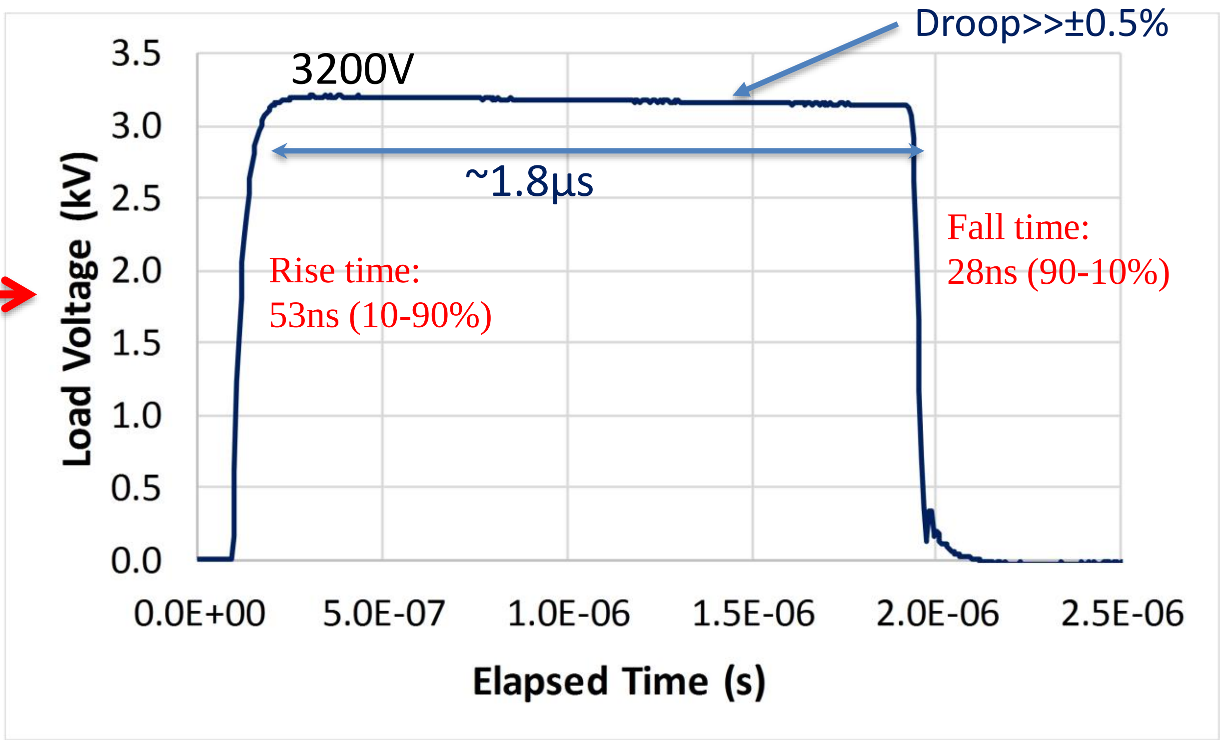


Four MOSFET Marx stages: measurements

*U*dc=800V, *R*load≈1.175Ω ⇨ ~2700 A expected:



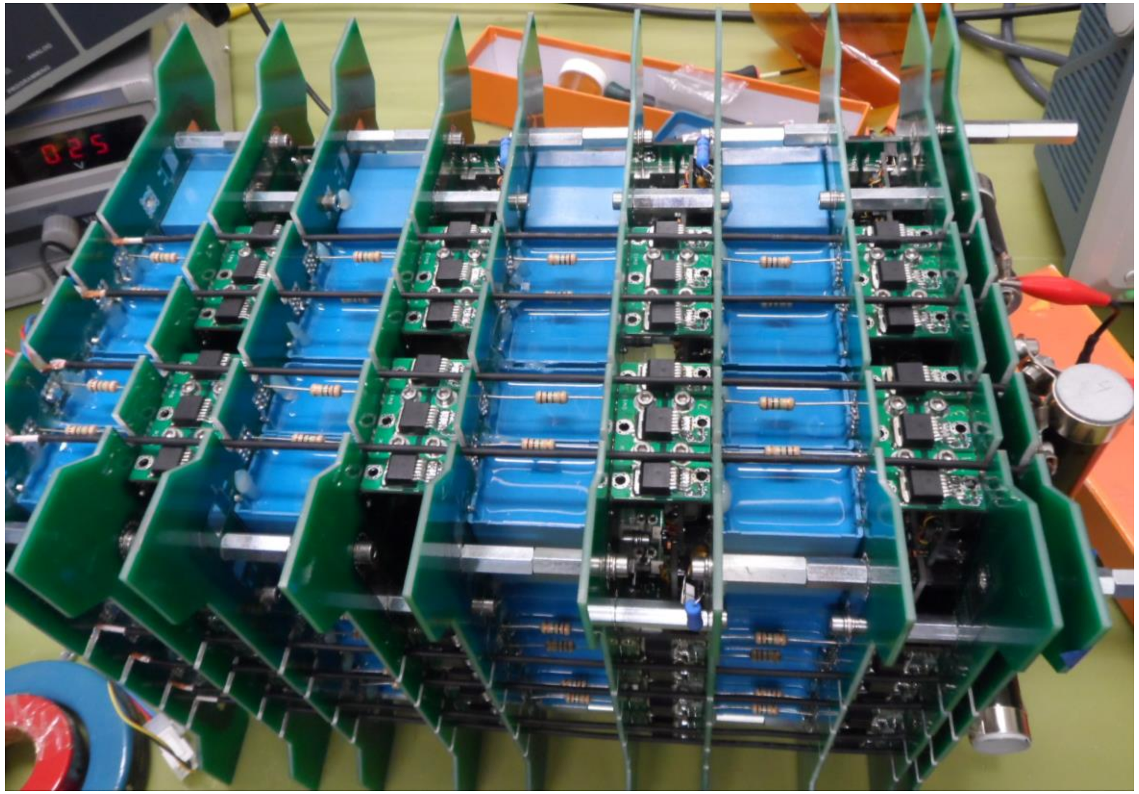
Measured load voltage:



Circuit time constant of 24 ns with a load of 1.175 Ω ⇨ four stage Marx circuit inductance of ~28 nH (~7nH/stage).

- ✓ **Current magnitude (2.7kA) meets specification (2.4kA),**
- ✓ **Current rise time (53ns, 10-90%) is in the right "ball-park" (75ns);**
- ✓ **Current flattop duration close to requirement (2μs).**

Solid-state Marx: ongoing R&D/challenges



- Studies to reduce flattop droop to within ±0.5%...
- Low inductance is achieved with four return wires on each side of Marx, close to "go" current paths:

  higher voltage ⇨ more clearance reqd. for insulation
  ⇨ higher circuit inductance
  ⇨ increased rise time
- Study of fault conditions (e.g. short-circuit in magnet) and limitation of current
- Study of possible failure modes of Marx generator
- Long-term reliability
- .....

Conclusions

ISEL & EPS have made very good progress carrying out R&D for a solid-state Marx generator for possible application to kicker systems:

- SiC MOSFETs, connected in parallel, can be used in fast high current pulsed power applications: good current sharing.
- Preliminary measurements with a solid-state Marx generator topology, with SiC MOSFETs, show that it is a promising candidate for generating fast, high current, pulses for kicker systems:
    - One stage @ 800V ⇨ 3200A
    - Four stages @ 3200V ⇨ 2700A: measurements show good performance (rise and fall).
- **The Marx generator topology is a promising candidate for replacing thyratrons and PFLs in kicker applications**.
- Future:
    - Assemble and test more stages and investigate the overall performance and reliability.
    - Long term operation with higher frequency;
    - Behaviour under fault conditions (e.g. short circuit).

Questions?

Thank you for your attention !

Questions ?

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