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# 4 MV 600kA Marx Generator Design with Closely Coupled sub-Marx

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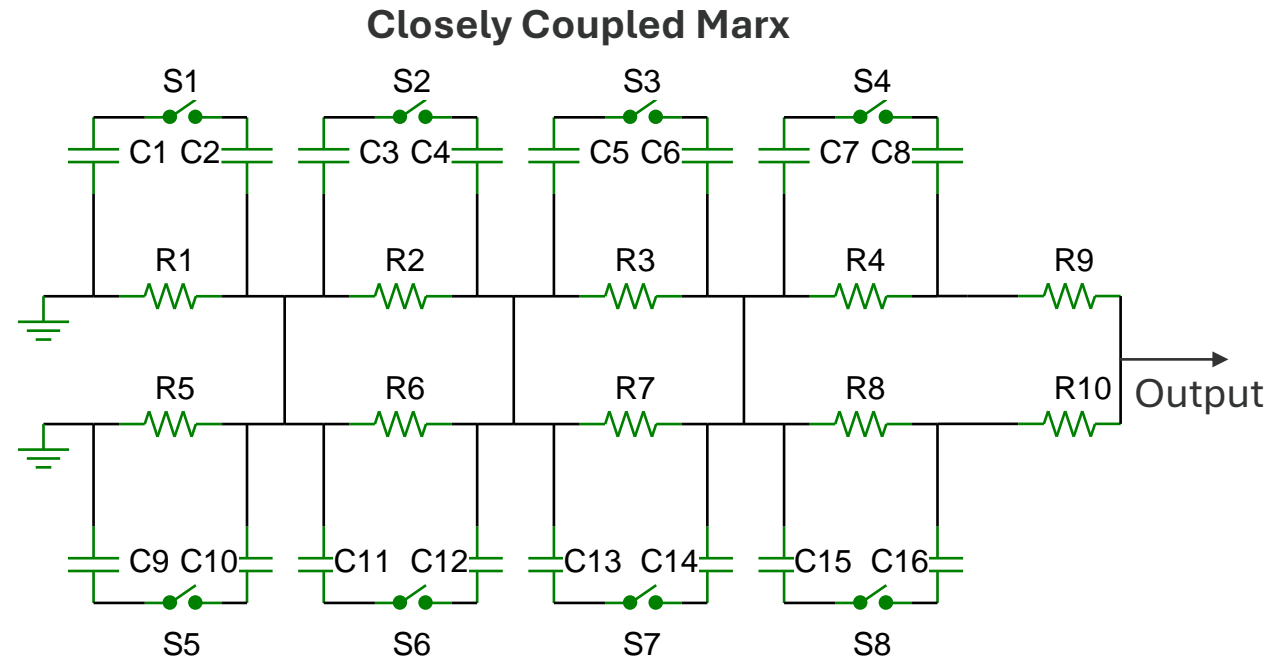
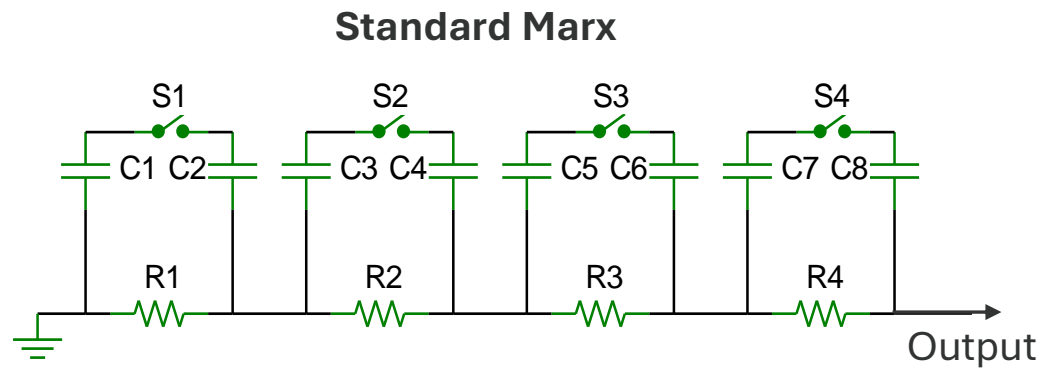
## ➤ Outline:

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- Closely Coupled Marxes
- Fast Marx considerations
- Simulations
- Conclusions

# What is a Closely Coupled Marx?

- In a CCM one side of the capacitors is electrically tied to a second sub-Marx.
- The switch pressures are set to hold off voltage only at the charging voltage level
- When the switches are triggered the additive voltage of the stages increases the voltage differential of the subsequent stages
- As the voltage pulse travels downstream the switch gaps self break



# Why use Closely Coupled Marxes (CCM)

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- A single sub-Marx with 26 stages at a charge of  $\pm 85$  kV will output a voltage of 4.4 MV into an open circuit
- The total Marx capacitance defines the current output
- By putting Marxes in parallel you can increase the total Marx Capacitance and increase the current output
- CCMs allow for a modular design that can then be combined in parallel in a single Marx tank
- Can be combined in multiple Marx tanks but output lines must be designed for specific configurations

## Lessons learned

- Quad Eagle Module testing has found that CCMs with a single stage connection between them reduces prefire jitter
- Higher coulomb transfer of PITHON Marx design vs QE Marx design necessitates a different Marx switch
- Output Marx connections need to have similar transit times to reduce loss from reflections
- This configuration works with low inductance capacitors and variations in output inductance marginally affect main output pulse peak voltage and can increase pulsewidth
- Charge collection and oil stirring are important factors to consider in design
- Oil quality for small gap spacing designs becomes a critical specification
- Electrostatic breakdown based on JCM equations works to guide design

# Large Format Switch

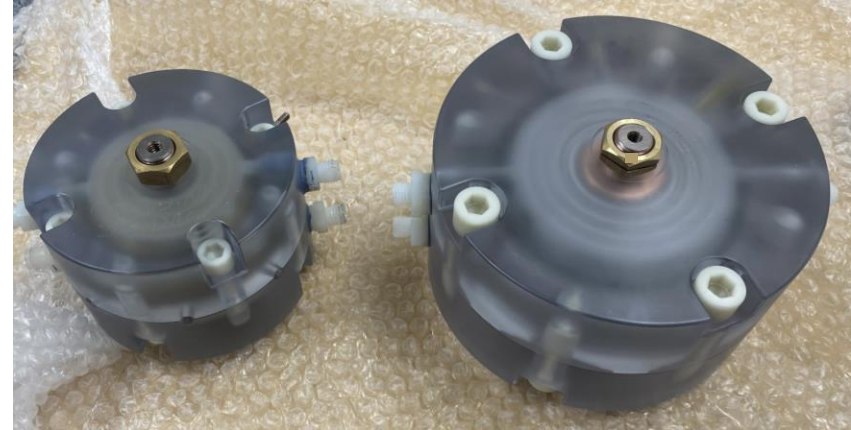
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## Design considerations

- Increase the gas volume this reduces the pressure impulse when switch is fired
- Decrease the peak field on the electrode surfaces
- Retain field uniformity across the switch as previous models
- Maintain housing manufacture quality standards to reduce leaks and cracking
- Improve oring seals to reduce leaks

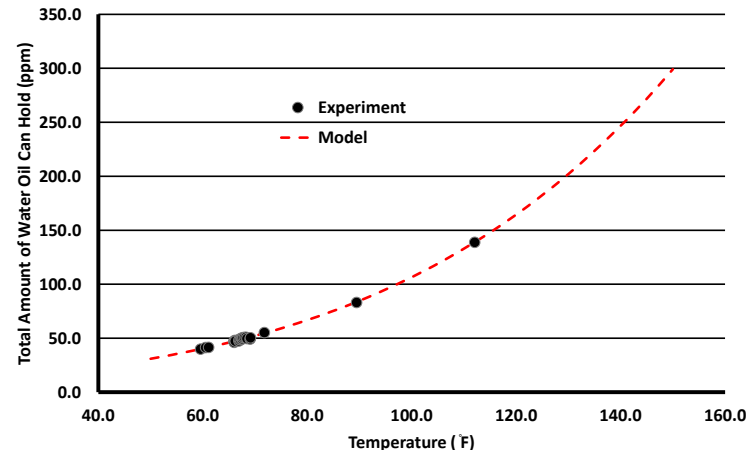
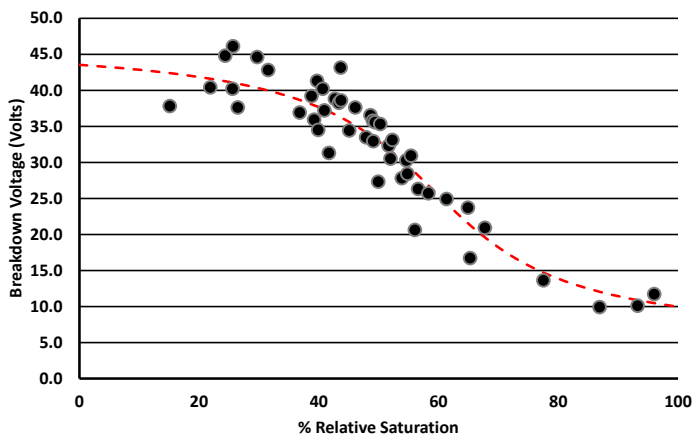
## Experimental testing

- Has been tested up to  $\pm 100$  kV
- Not yet a commercial product
- Mechanically rated for high pressure (150 psig) dry air
- Predicted larger coulomb transfer than previous models  $>100$  mC



# Oil Quality

- The fast Marx CCM design requires smaller gaps between charging and triggering lines, capacitors, and switches.
- The standard quality of the oil has been set to attempt to achieve  $>38$  kV/0.1" (ASTM D1816) during all operational modes.
- There are a range of factors such as water content, oxidation, and HV exposure which contribute to the gradual polarization of the oil which degrades the voltage holdoff levels
- Water content and temperature are measured routinely to refine calculation models
- Full Oil Sampling Analysis carried out periodically
- Percent Relative Saturation point is a key factor
  - Warmer oil can hold more water per volume and the holdoff voltage becomes more resilient
  - Colder oil can hold less water per volume and the holdoff voltage becomes less resilient



Fisica has designed and developed a portable vacuum dehydrator that is available for purchase to reduce water content and increase voltage holdoff in any pulsed charged system

# Modeling of Fast Marx CCMs

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## Circuit Models and Optimization Studies

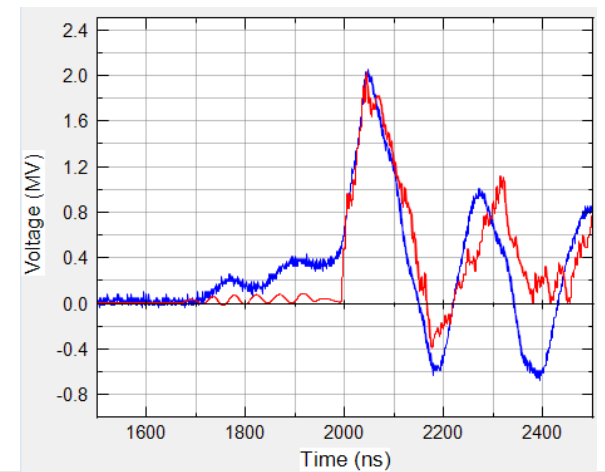
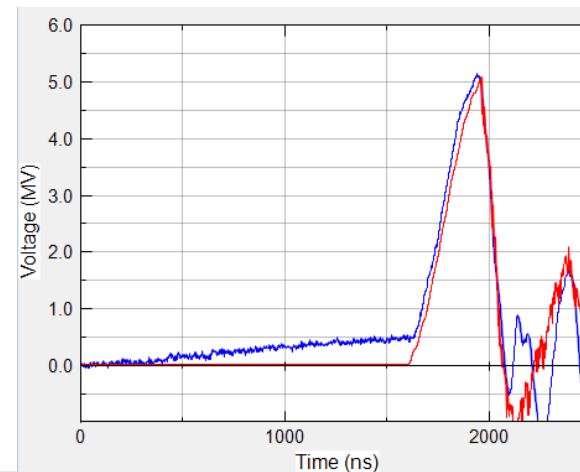
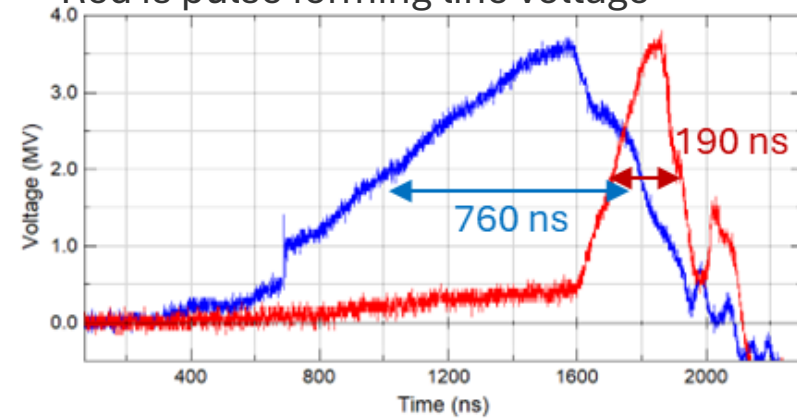
- Marx phase variations
- Negative and positive charging
- Pre-fire
- Electro-static analysis using Quick Field and CST Studio Suite e-static solver
- CST
  - Time domain solver
  - Particle In Cell (PIC)
  - Tracking solvers

# Fast Marx Allows Removal of Water Switch Compression Stage

- PITHON II design removes single water switch gap which is a large source of jitter and water shock
- Castle Simulations benchmarked to QE CCM design allows for accurate modeling
- Reduces water needed for the system



Blue is transfer capacitor waterline voltage  
Red is pulse forming line voltage

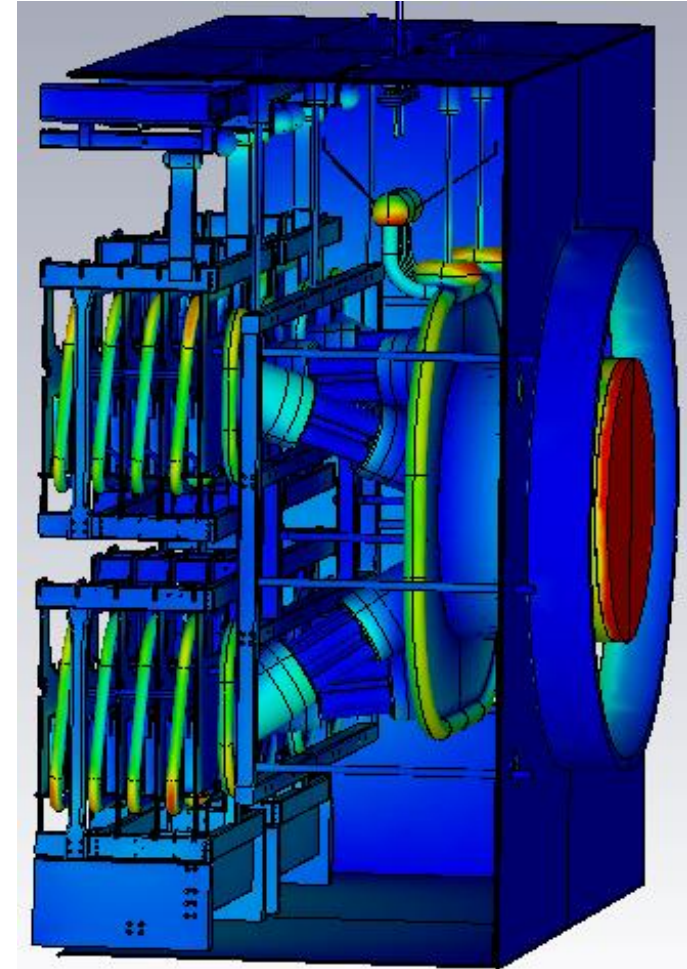


Blue traces are experimental data from PITHON  
Red Traces are Castle simulation

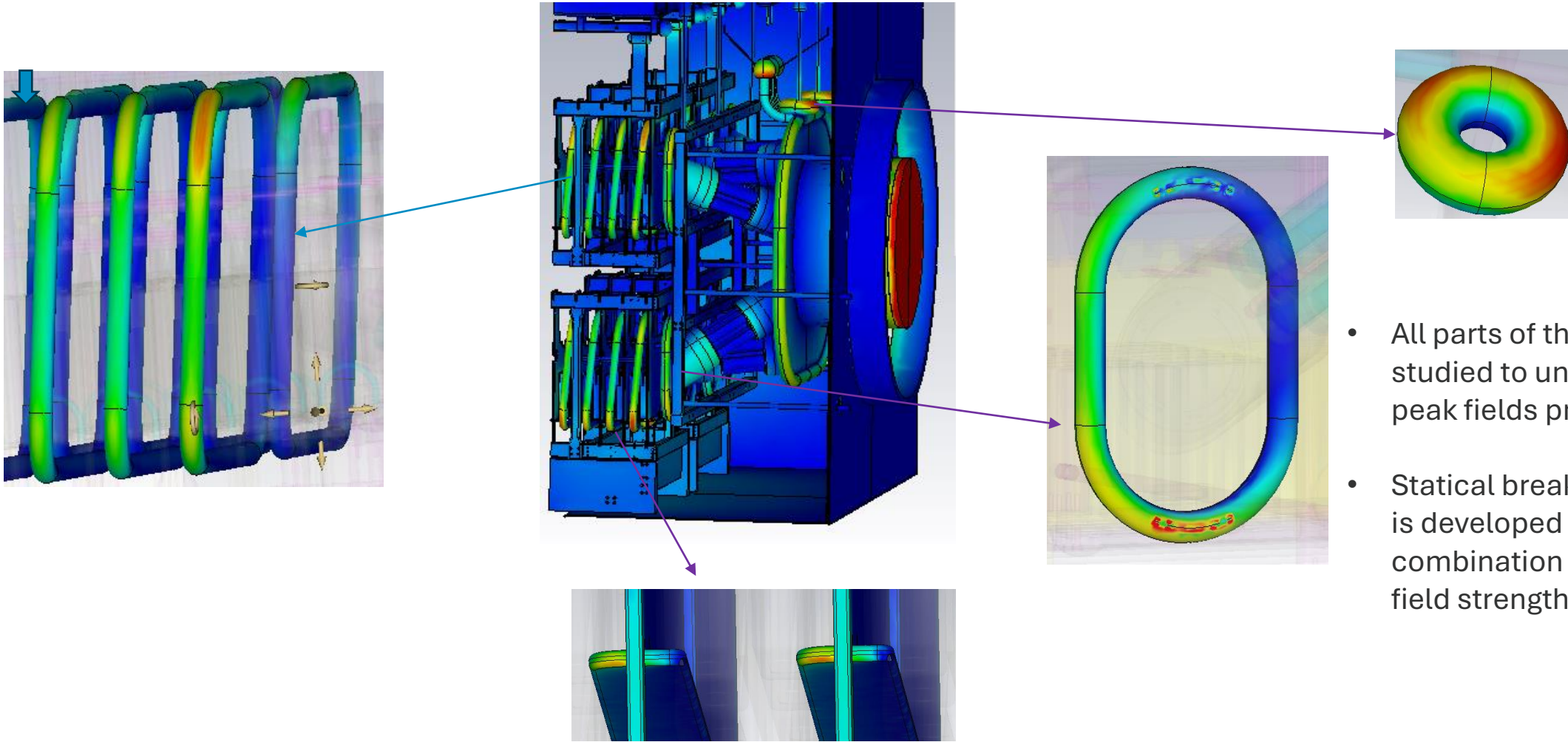
# Combining Fast Marxes

## Combining Fast Marxes design considerations

- Equalize the transit time
- Output series resistance protects each components from reflections
- Distance from High Voltage components to ground sources
- Hoops used to grade fields and collect charge
- Electrostatic and electrodynamic studies to understand power flow



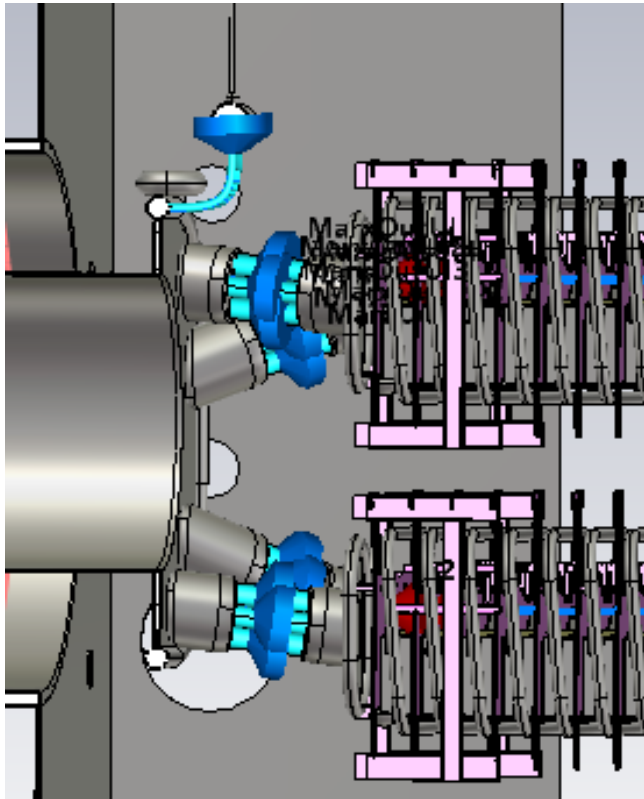
# Electrostatic Simulations of 4 MV Marx



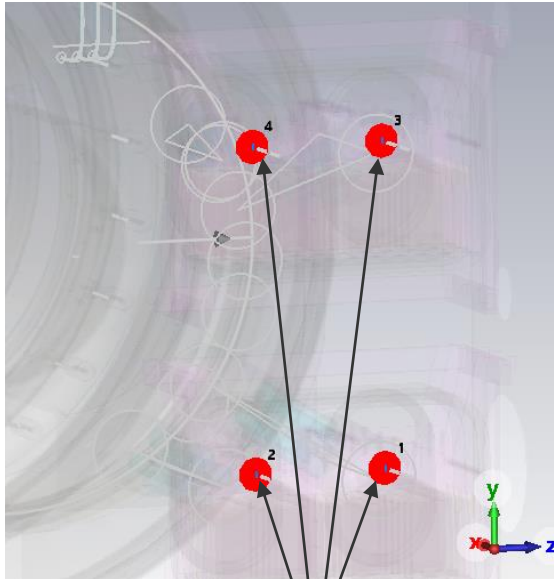
- All parts of the Marx are studied to understand the peak fields produced
- Statical breakdown criteria is developed from a combination of area and field strength

# Time-domain Simulations of 4 MV Marx

Used for various design optimization and failure mode analysis



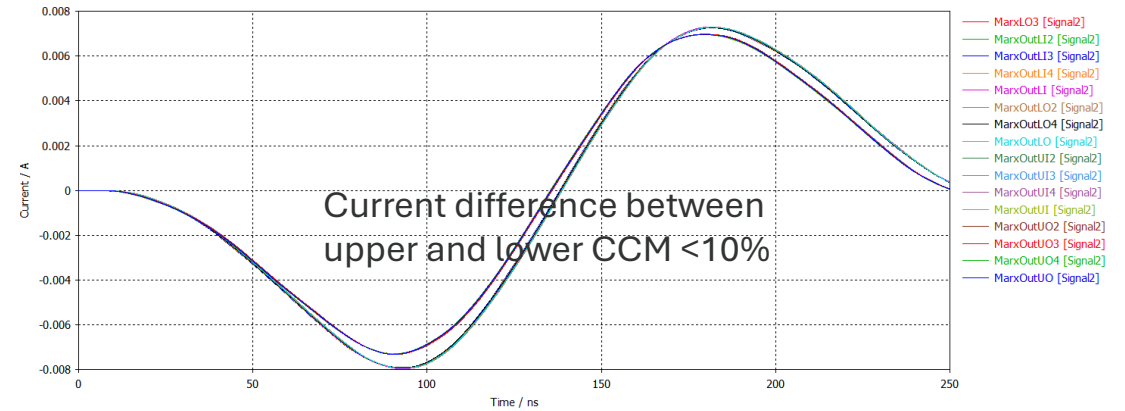
Model view



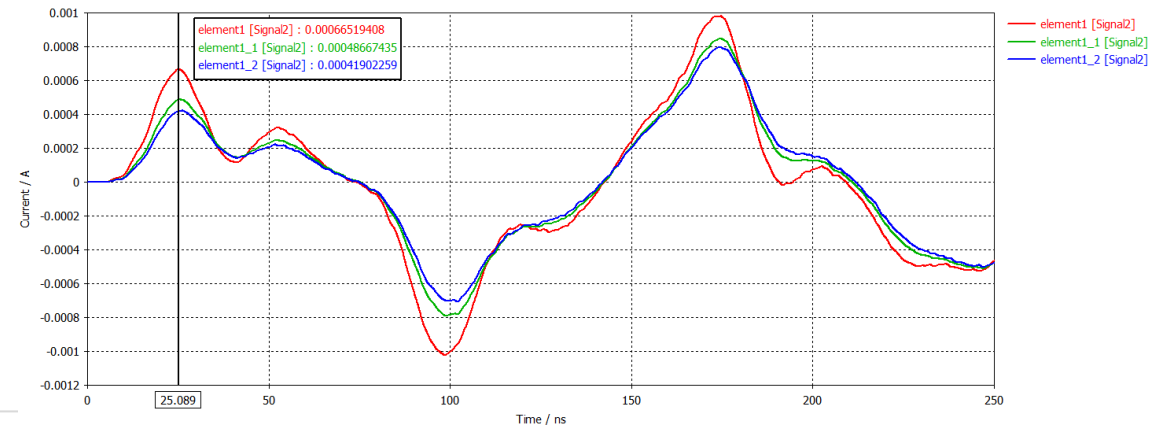
Excitation ports

- Excitation signal is injected at each sub-Marx (two per CCM)
- Allows to study effects of jitter, prefire etc with this configuration

- Design optimization was made to ensure the output from each CCM/sub-Marx are close to each other



- Simulated current/voltage distribution between individual resistors to ensure the specifications for manufacturing is good.



# Conclusions

Fast Marxes have now been used to build a suite of simulators for various applications with nanosecond timescale outputs  
Modeling and design have been improved through benchmarking to existing working systems  
Modular design allows for designs to include high voltage (1-4 MV) and high current applications (kA-MA scale)  
Fisica can build and design Blumlein designs or inductive voltage adders using this technology

	Year online
DTRA SPG	2016
Lockheed Martin 428	2018
Honeywell 430	2020
WSMR PGS	2023
NSWC Crane SPG	2024
DTRA Quad Eagle	2025
PITHON II (proposed)	2027

