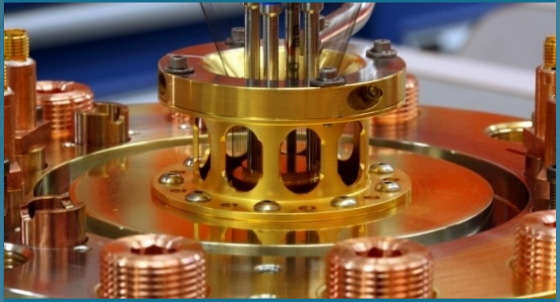
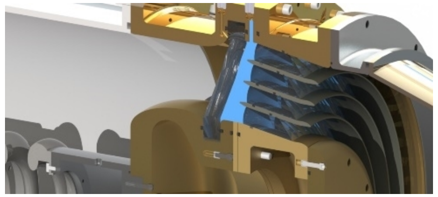
SAND2023-05552C

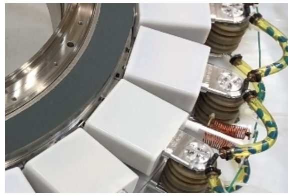
Sandia National Laboratories

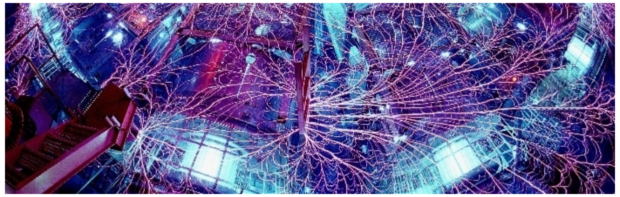
Design and commissioning of Vulcan

A testbed for Fast Marx generator and vacuum insulator development









Brian Hutsel, Brian Stoltzfus, Mark Savage,
Owen Johns, Eric Breden, Mike Sullivan

2023 Pulsed Power Conference

San Antonio, Texas

June 25-29 2023

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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Outline

Introduction

Mission need

Vulcan design

Commissioning experiment results and simulations

Initial vacuum insulator tests

Future plans

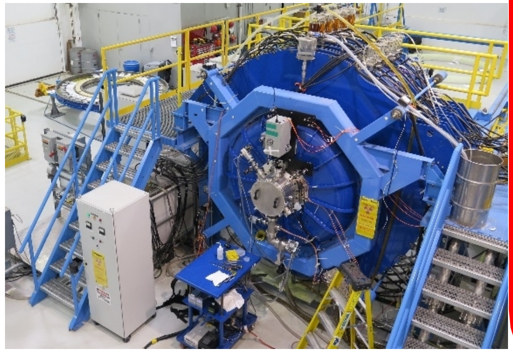
Conclusion

Introduction – Pulsed power facilities at Sandia

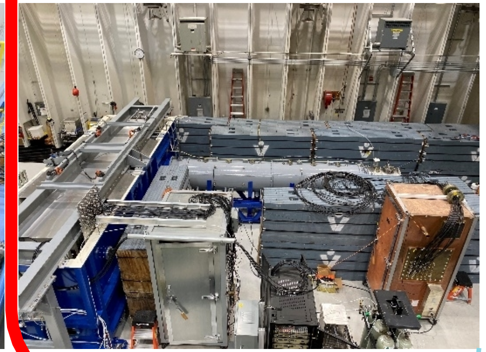
- Vulcan is an intermediate-scale test facility at Sandia.

Thor
76 kJ
2-3 MA, pulse-shaped

Mykonos
72 kJ
1 MA, 100 ns

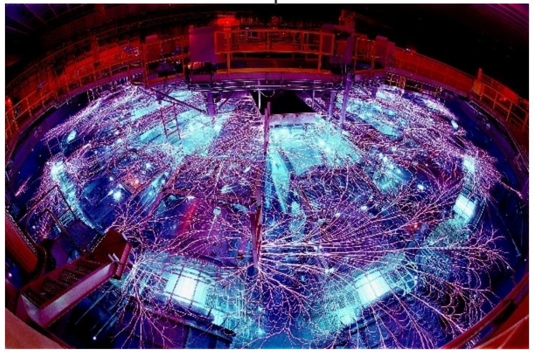


Vulcan
20 kJ
5.5 MV

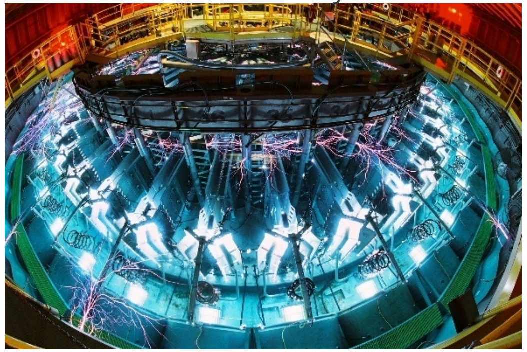


Large Scale — Intermediate Scale — Small Scale

Z
20 MJ
26 MA Z-pinch

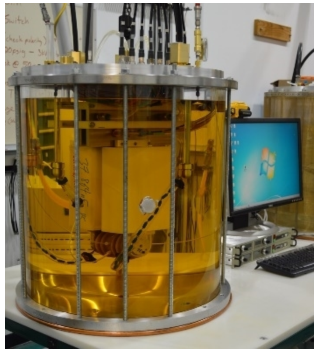


Saturn
5.6 MJ
1-2 MeV x-ray



Hermes
1.5 MJ
18 MeV gamma ray

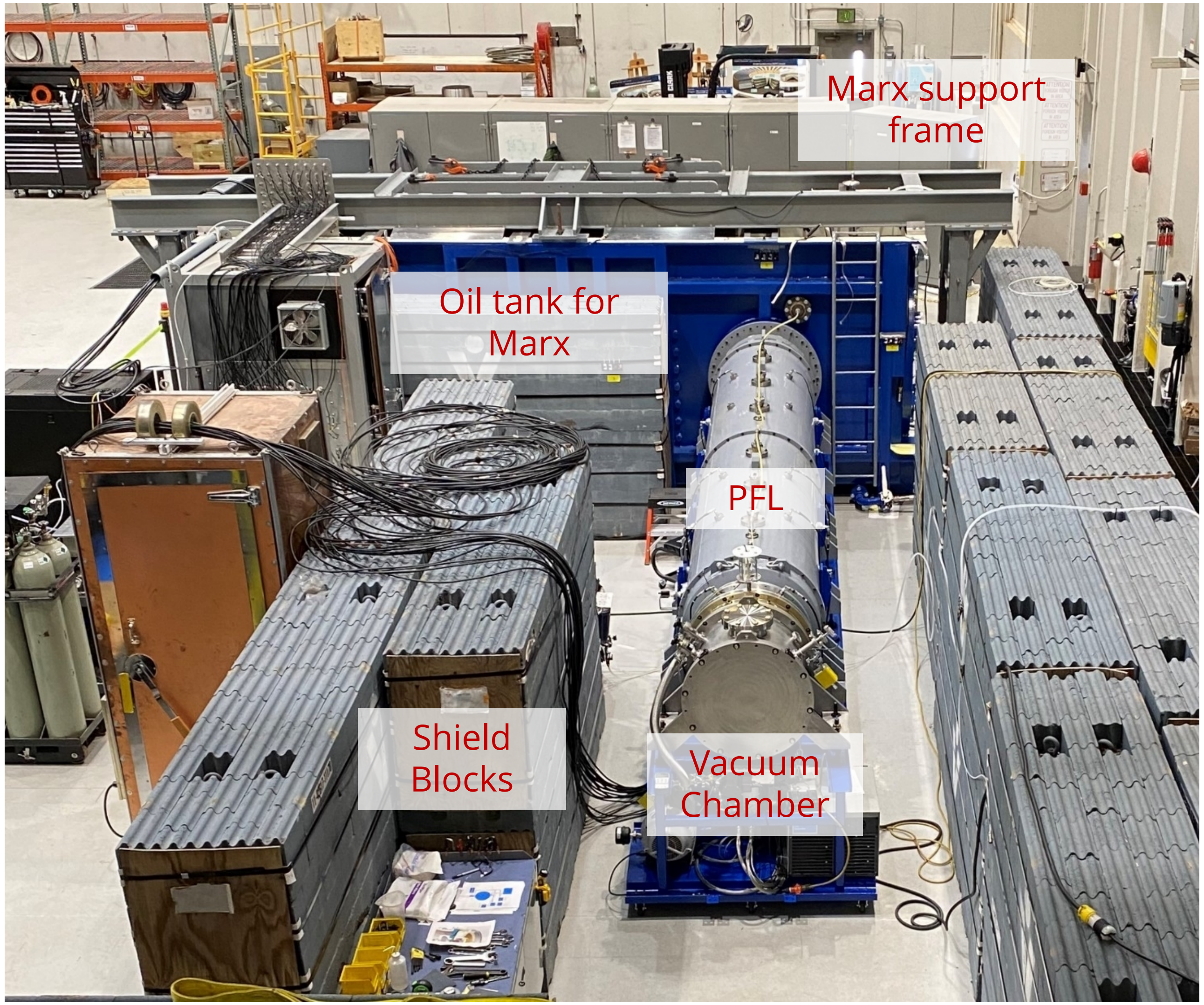
Switch Tester
up to 800 J
+/- 100 kV



Caeculus
400 J
500 kV

Vulcan Overview

- New experimental capability for technology development and evaluation at scales relevant for next-generation pulsed power drivers.
- Primary Mission: vacuum insulator testing
  - Large area, 1000-4000 cm^2, vacuum insulator testing at up to 5 MV.
- Secondary Mission: evaluation of Fast Marx technology.
  - Fast Marx system at higher voltage/current than previously demonstrated at Sandia.



Vulcan lab space

Need for vacuum insulator testing

- Vacuum insulator performance is a large driver of facility size/cost.
- Flashover probability dependent on electric field stress, area, and time:

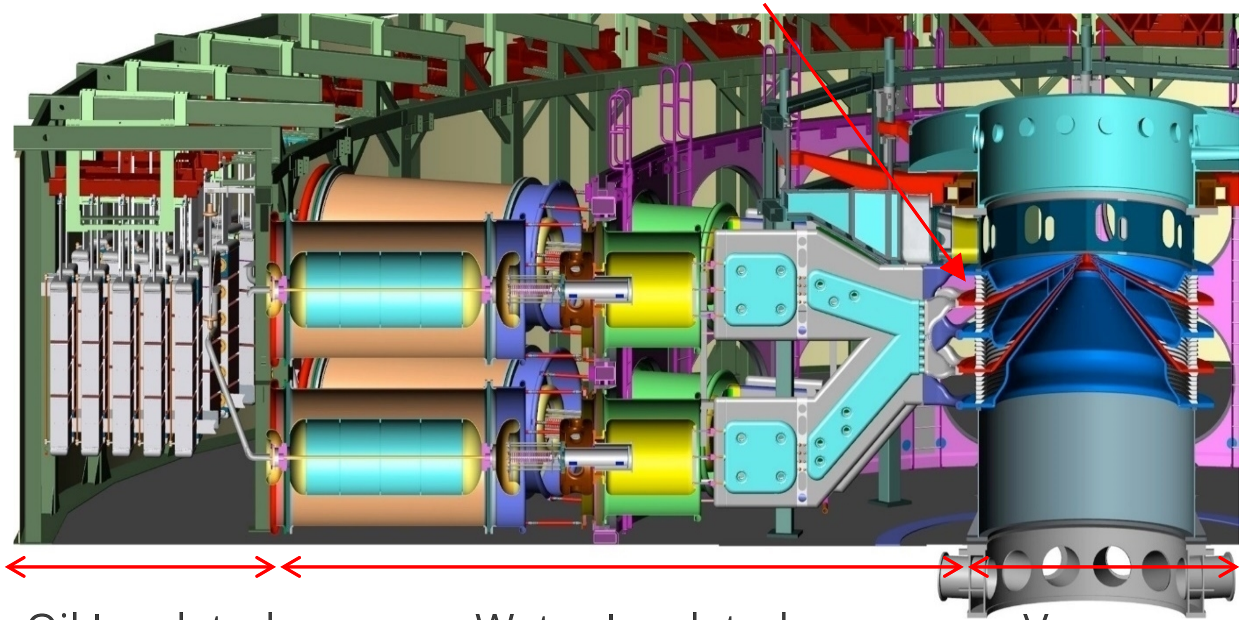
JCM:

$$p = 0.5\left[F t^{1/6} A^{1/10}/175\right]^{10}$$

Stygar:

$$p = 1 - \exp\left[-\left(\frac{F}{260}\right)^{10} t \frac{C \ln 2}{\left(\exp\left[\frac{.24}{d}\right]\right)^{10}}\right]$$

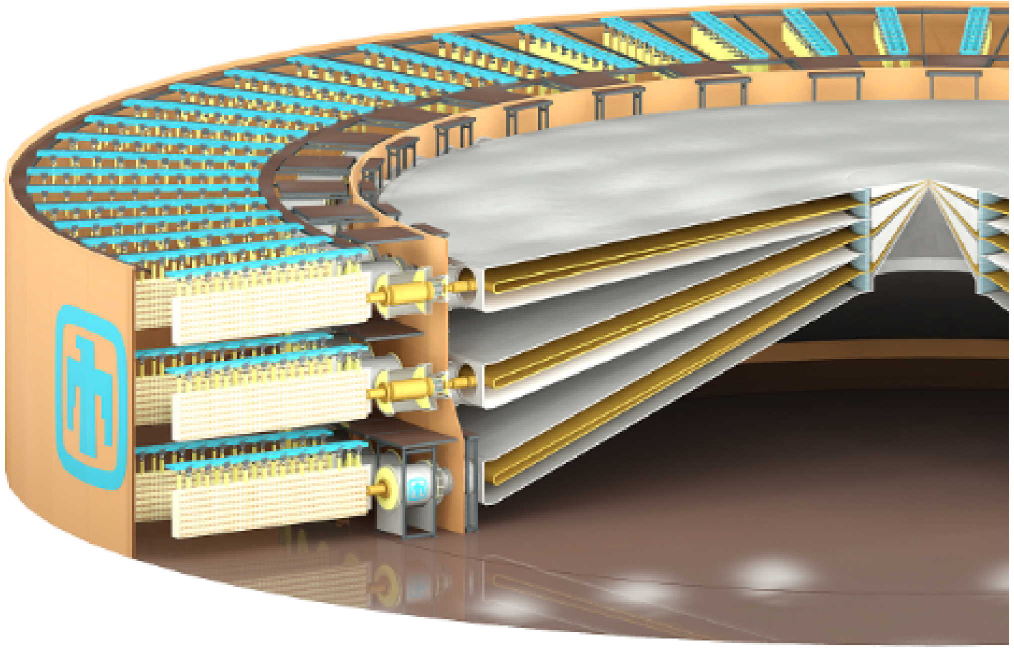
- Testing at relevant electric fields, areas, timescales minimizes scaling for future facilities



Z accelerator

Fast Marx technology evaluation

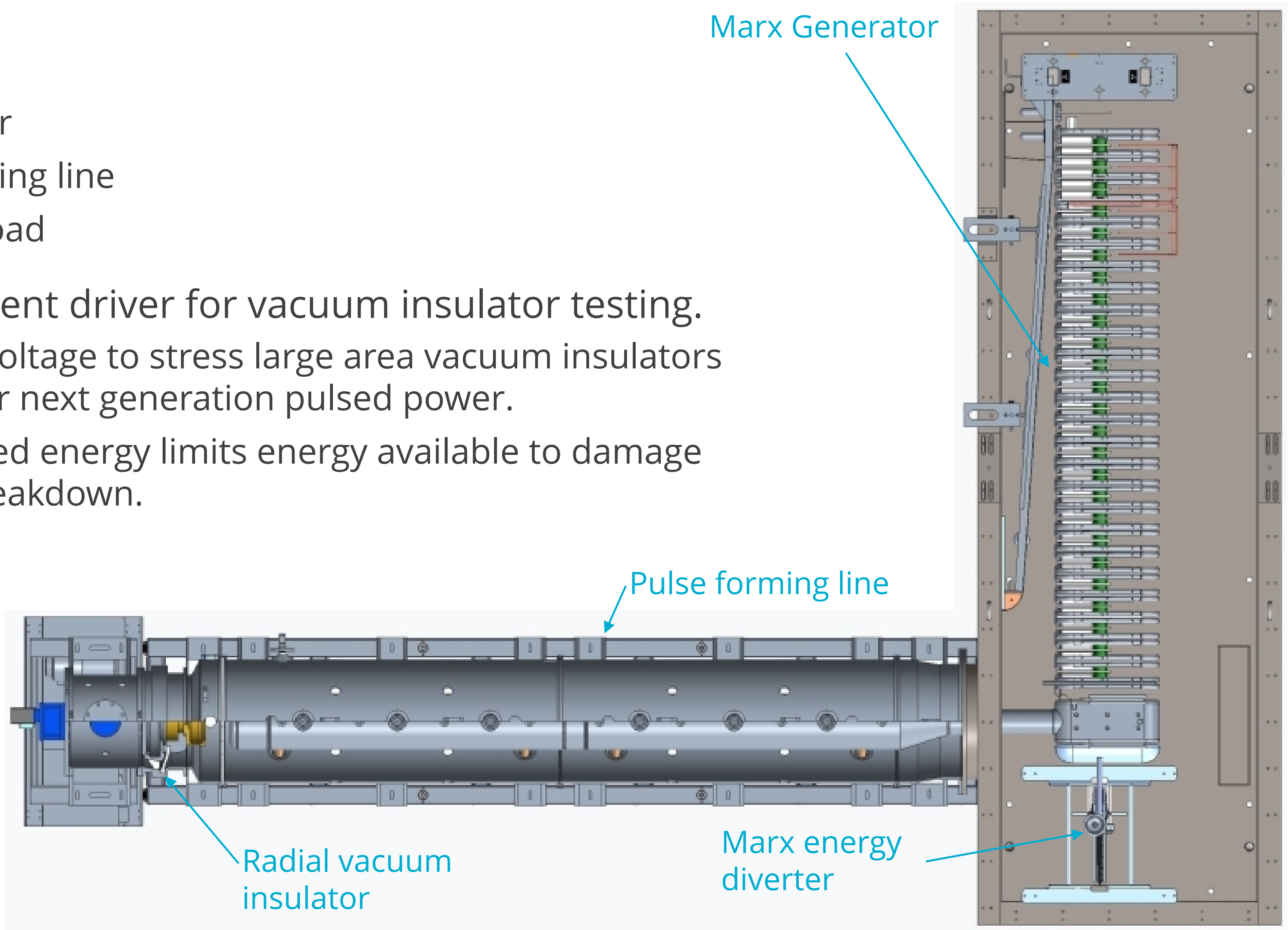
- Next-generation pulsed power facility size may be reduced if a Fast Marx is used as the primary energy storage
  - Eliminates at least one stage of pulse compression. Large intermediate store capacitors and laser-triggered gas switches.
- Fast Marx technology has not been demonstrated on a large scale, unlike conventional Marx generators.
- Vulcan is the largest Fast Marx system demonstrated at Sandia



NGPP concept based on Fast Marx primary energy storage

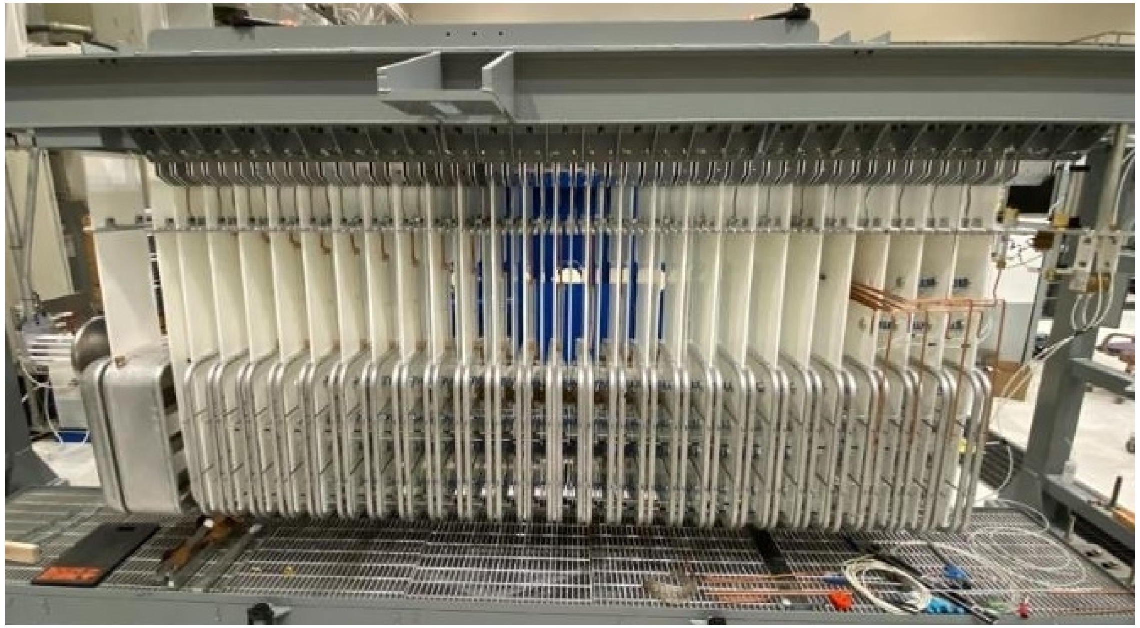
Vulcan Overview

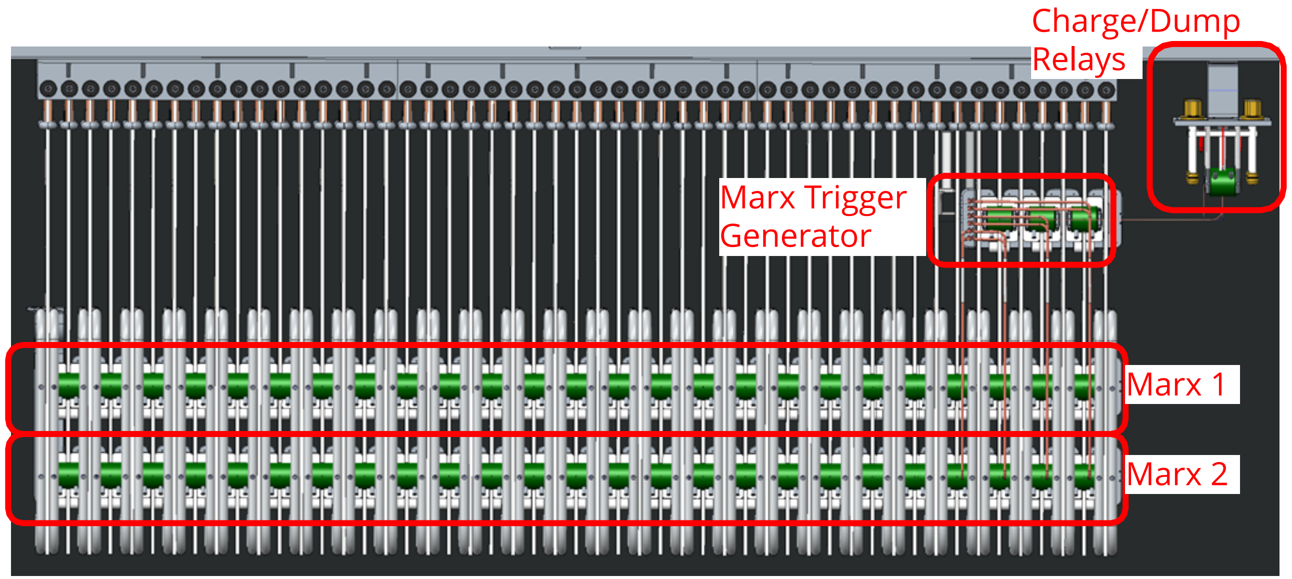
- Vulcan consists of:
  - Fast Marx generator
  - oil-filled pulse forming line
  - vacuum insulator load
- High voltage, low current driver for vacuum insulator testing.
  - Output necessary voltage to stress large area vacuum insulators to relevant fields for next generation pulsed power.
  - Reducing total stored energy limits energy available to damage insulator during breakdown.



Vulcan Marx

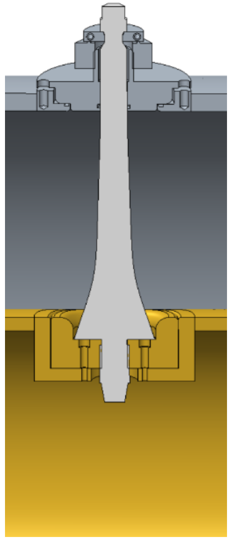
- Marx generator consists of 2 parallel linear Marxes in a layout we call a Fast Marx array (FMA).
- Marx consists of 25 stage bi-polar charged stages.
  - Stages comprised of two 100 kV, 40 nF capacitors
  - 200 kV, dry air insulated gas switch
- 20 kJ stored energy at maximum +/- 100 kV charge voltage
- C = 1.6 nH, L = 1.7 μH
  - $\sqrt{LC} = 52\,ns$
- 5 MV open circuit output voltage

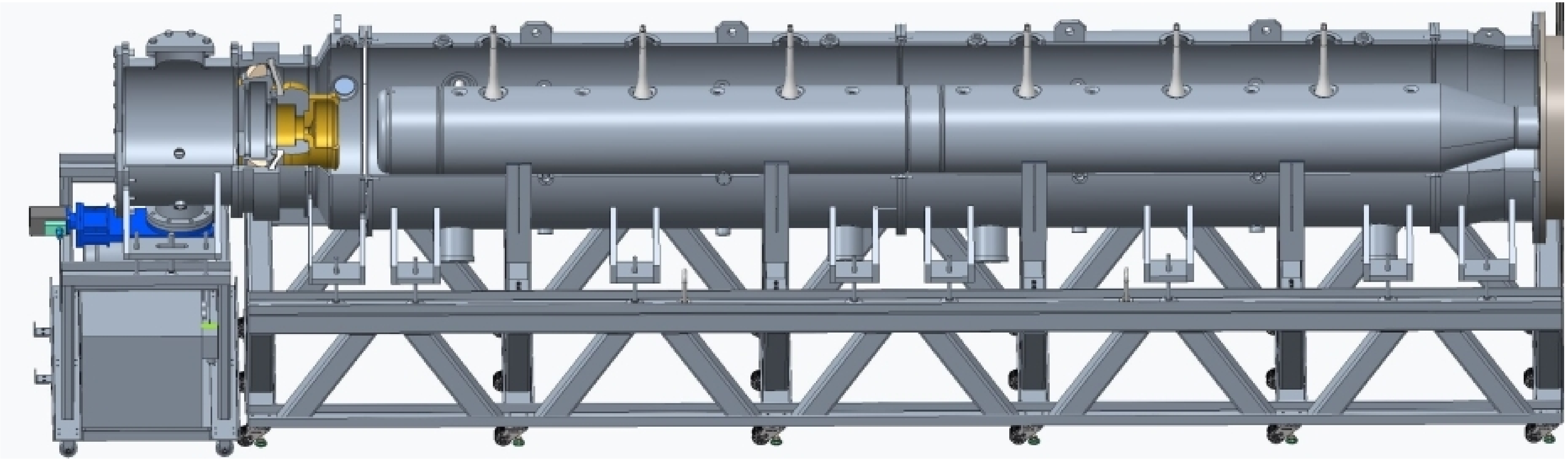




Pulse Forming Line (PFL)

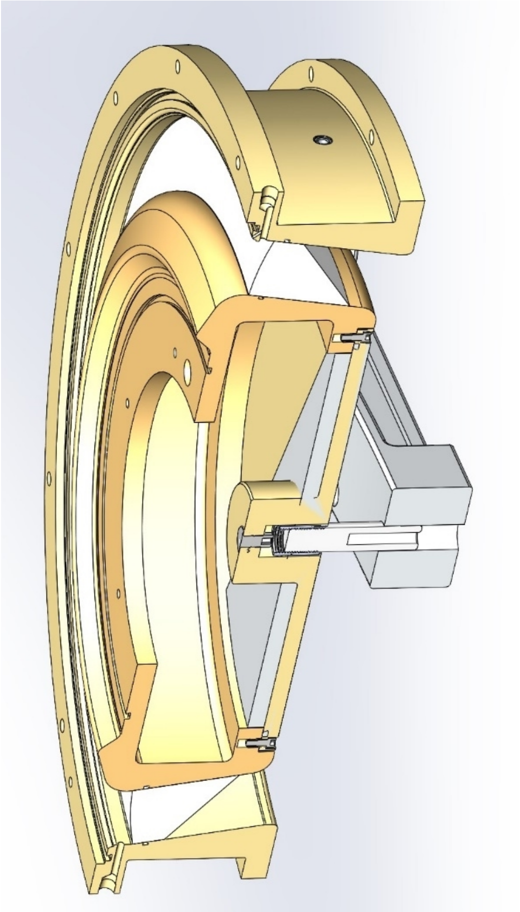
- Coaxial, oil-filled PFL
  - Z=30 Ω, τ=24 ns, C=800 pF
- Conservatively designed
  - Peak E-field at 5 MV: 365 kV/cm at cathode, 168 kV/cm at anode.
  - Derated from peak allowable fields of 620 kV/cm at cathode, 390 kV/cm at anode.
- Manually adjustable output switch gap to vary insulator stress time
- PVDF (polyvinylidene difluoride) insulator support rods
  - Relatively high dielectric constant (ε_r~10) and shaped profile reduces peak E-field near insulator.



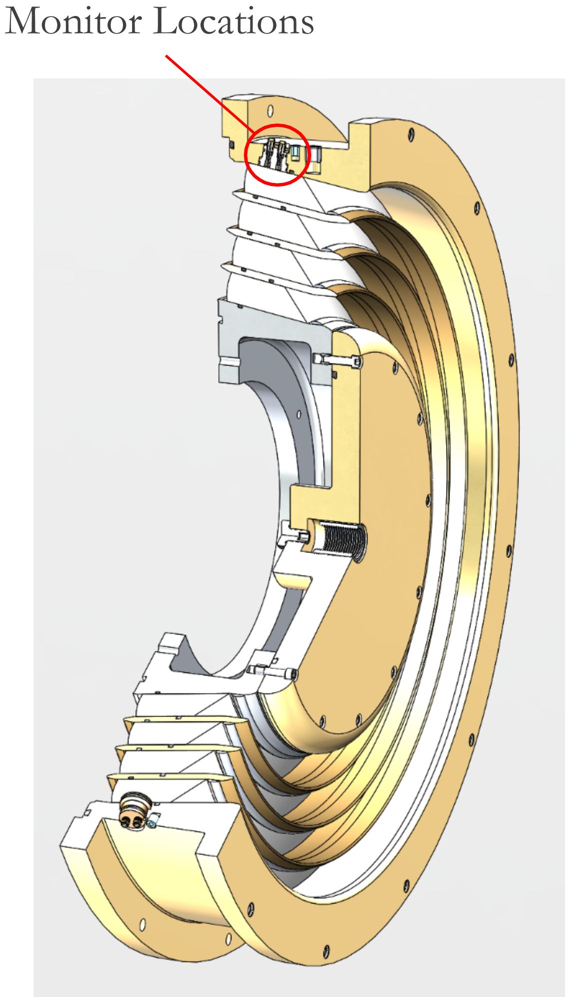


Initial vacuum insulator experiments

- Continue previous vacuum insulator testing done on Sphinx.
  M. E. Savage – Performance of a Radial Insulator Stack – 2015 PPC
- Radial insulator stack, up to four rings.
  - Multiple insulator shapes
  - 5 - 10 cm insulator length
- Assuming γ_{SM} = 260, t_{eff} = 20 ns
  - Single Stack operates at ~1.4 MV
  - Quad Stack operates at ~2.3 MV



Single Ring
d = 5.715 cm
1200 cm^2



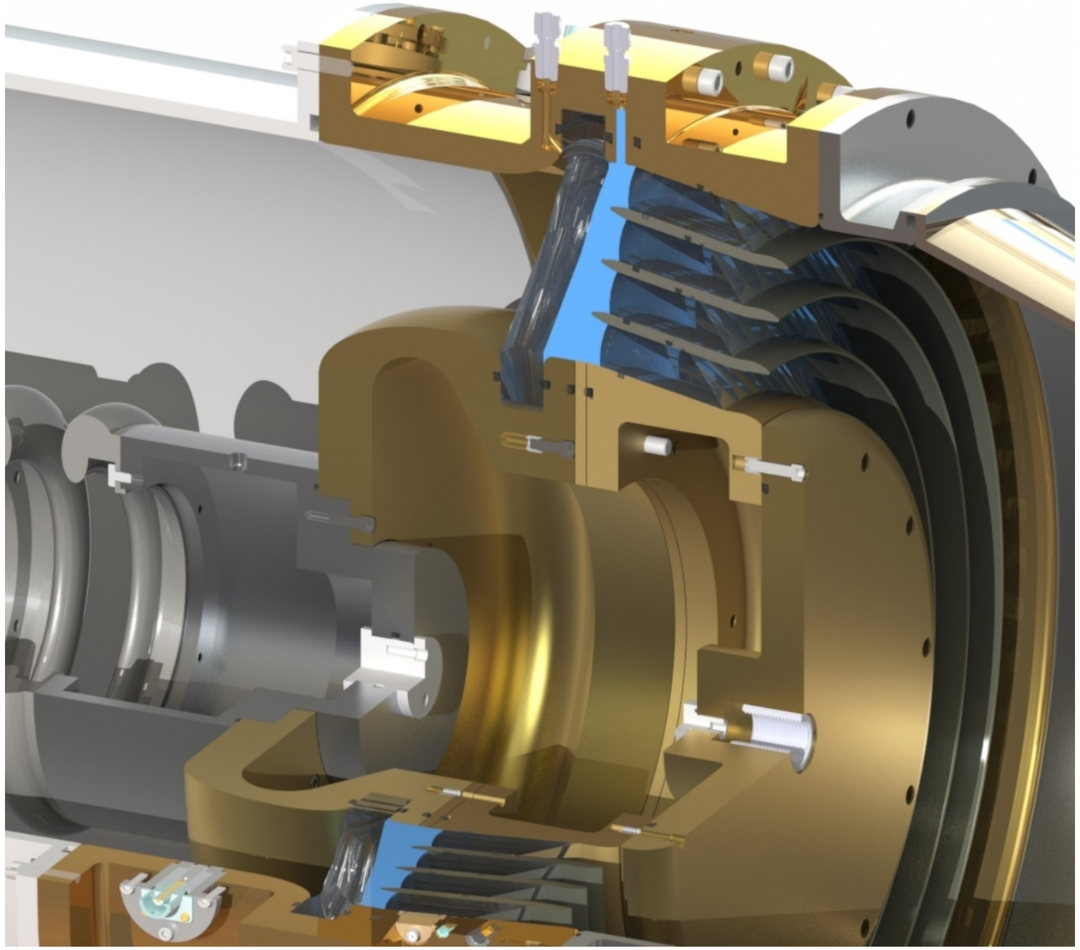
Quad-Stack
d=10.16 cm
2300 cm^2

Initial vacuum insulator experiments

- Radial insulator stack:
  - Easily coupled to coaxial PFL geometry
  - Provides easy access for insulator refurbishment.
  - Radial insulator stacks require field grading
- Water lens, within oil insulated PFL, grades the fields uniformly.

Insulator number	Voltage deviation, % (with lens)	Voltage deviation, % (no lens)
1	+0.2	-28
2	+0.6	-12
3	-0.3	+8
4	-0.4	+32

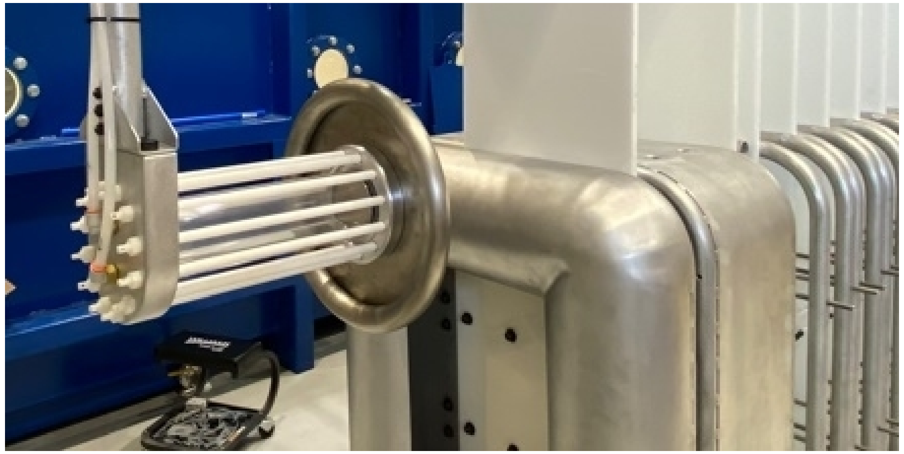
- Water lens contributes significantly to stack capacitance, potentially loading down driver.
  - Quad Stack: C ~ 290 pF
  - Single Ring: C ~ 600 pF



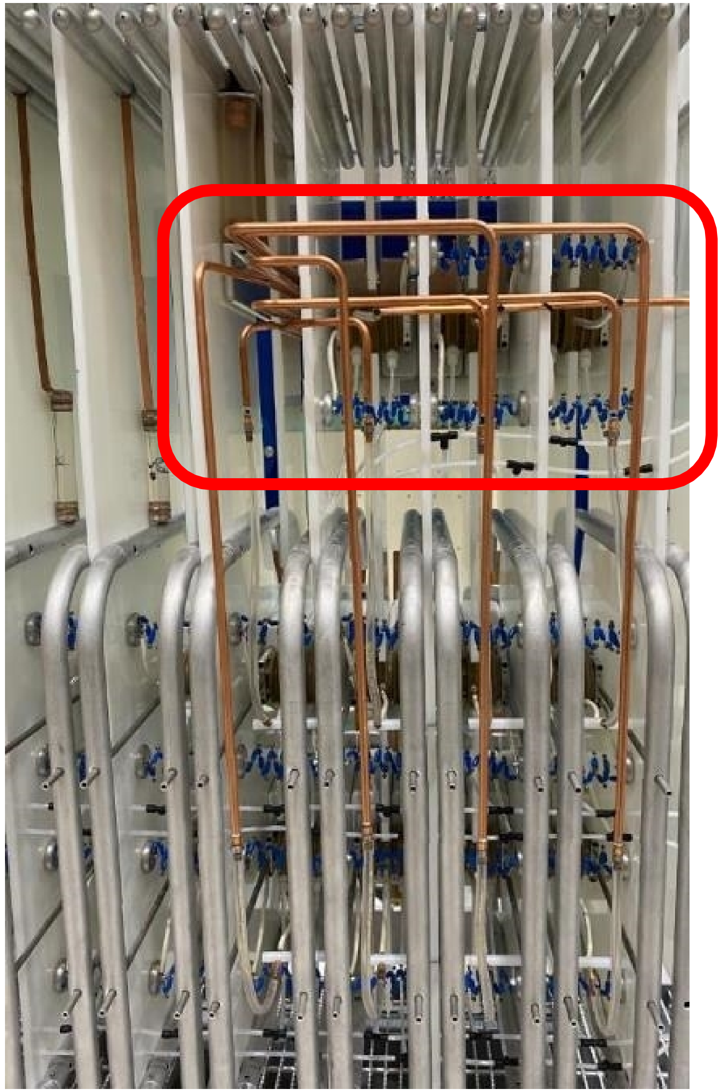
Quad-Stack assembly with water lens

Additional system components

- Marx Trigger Generator (MTG) integrated into support structure
  - 3 stage Marx, independently charged from main Marx
  - Currently configured to trigger first four stages of the FMA.
  - Remaining stages self-break with floating trigger electrodes.
- FMA and MTG each have energy diverters
  - Oil switch and water resistor.
  - Switch gaps adjusted to close after PFL reaches peak voltage
  - Energy diverter resistors sized to dissipate full energy of MTG or FMA for subsystem tests.



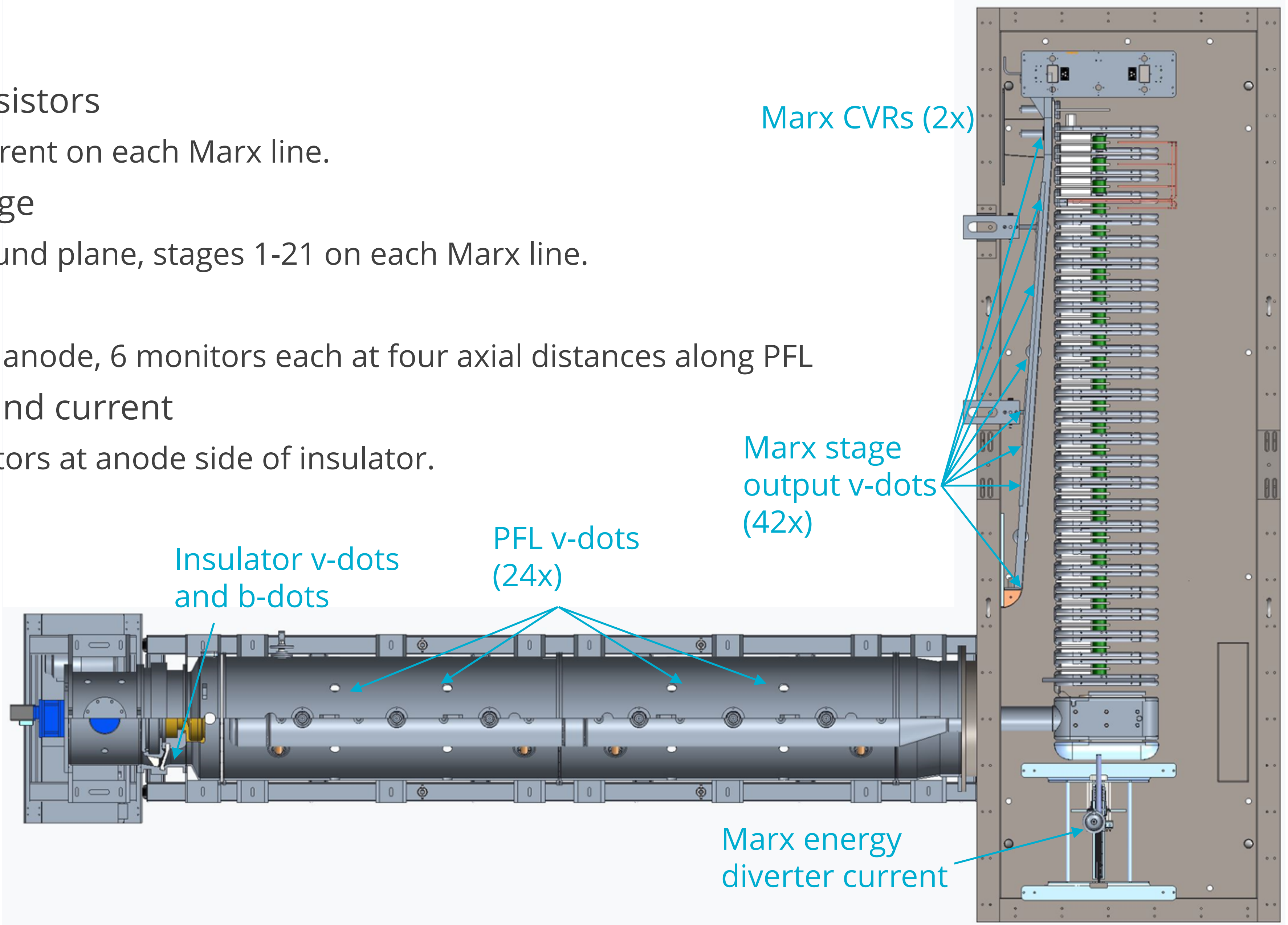
Primary Energy Diverter



MTG

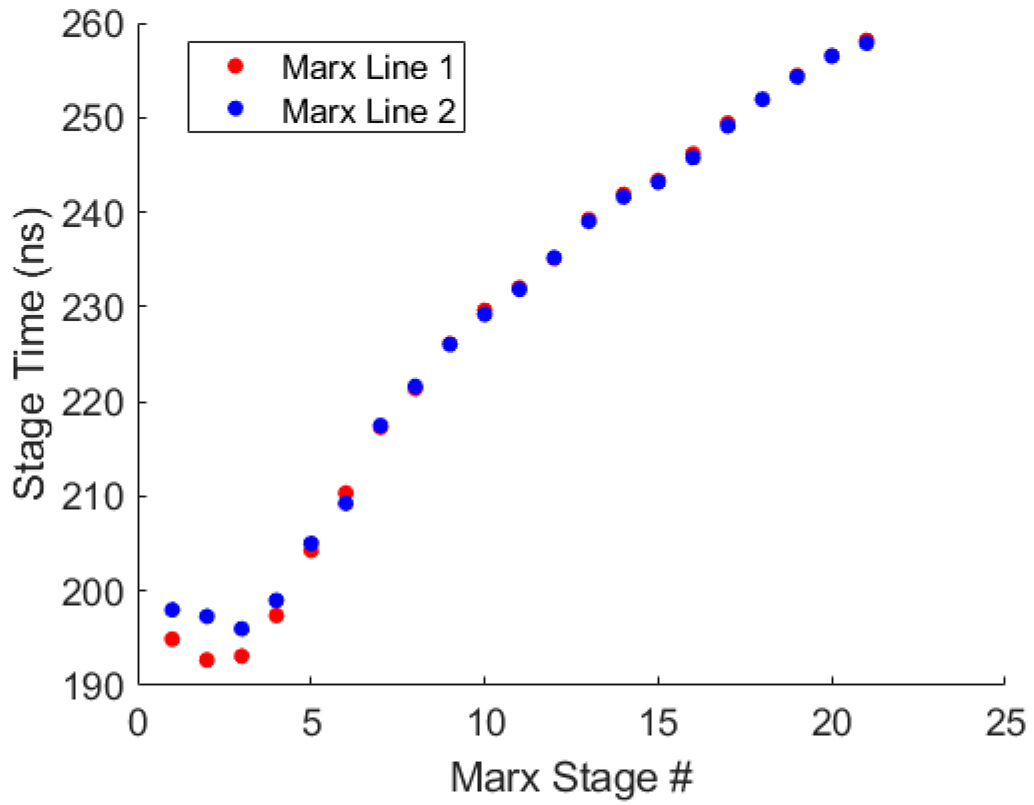
Diagnostics

- Marx current viewing resistors
  - Ground side Marx current on each Marx line.
- Marx stage output voltage
  - V-dot monitors in ground plane, stages 1-21 on each Marx line.
- PFL voltage monitors
  - V-dot monitors in PFL anode, 6 monitors each at four axial distances along PFL
- Insulator stack voltage and current
  - V-dot and B-dot monitors at anode side of insulator.



Initial FMA – PFL tests

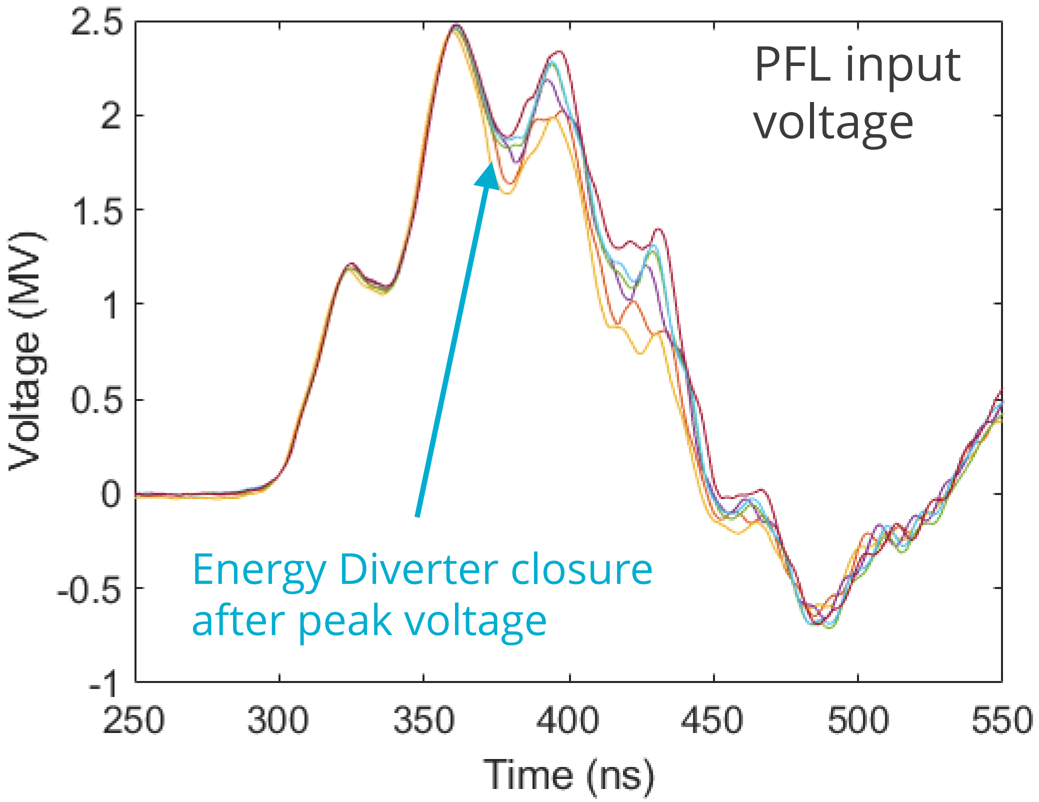
- 30 shots conducted without a vacuum insulator load to verify performance of MTG, Marx, and energy diverters
- Marx tested up to 50 kV Marx charge voltage (5 kJ stored energy)
  - Sufficient for continuation of previous insulator tests, up to 2.5 MV applied.
- Marx erection monitored with Marx stage output voltage monitors on stages 1-21.
  - Stages 1-4 triggered by MTG.
  - Stages 5-25 self-break.
  - Marx erects in ~60 ns.
  - Early self-break stages close noticeably slower than late stages.

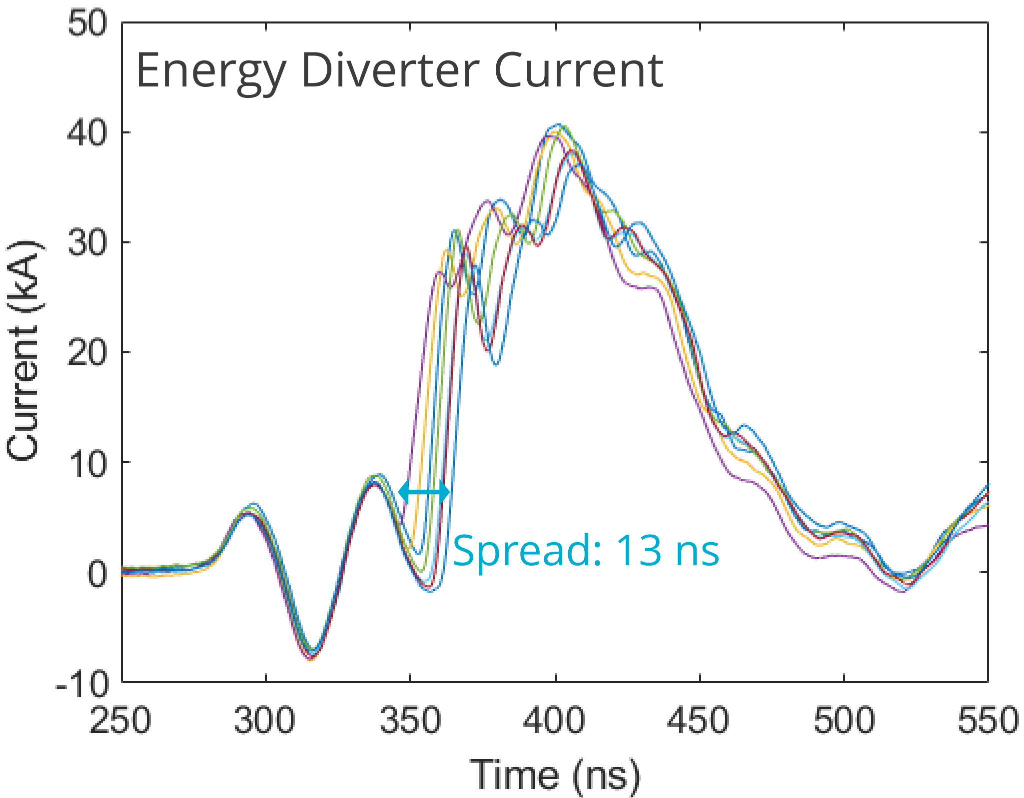


Plot of stage closing times vs. position along the FMA (Stage 1=ground, Stage 25=output) ~60 ns erection time

Initial FMA – PFL tests

- Verify performance of MTG, Marx, and energy diverters – no vacuum insulator.
- Conducted with up to 50 kV Marx charge voltage
  - Sufficient for continuation of previous insulator tests, up to 2.5 MV applied.
- Output voltage and energy diverter closure is consistent shot-to-shot.

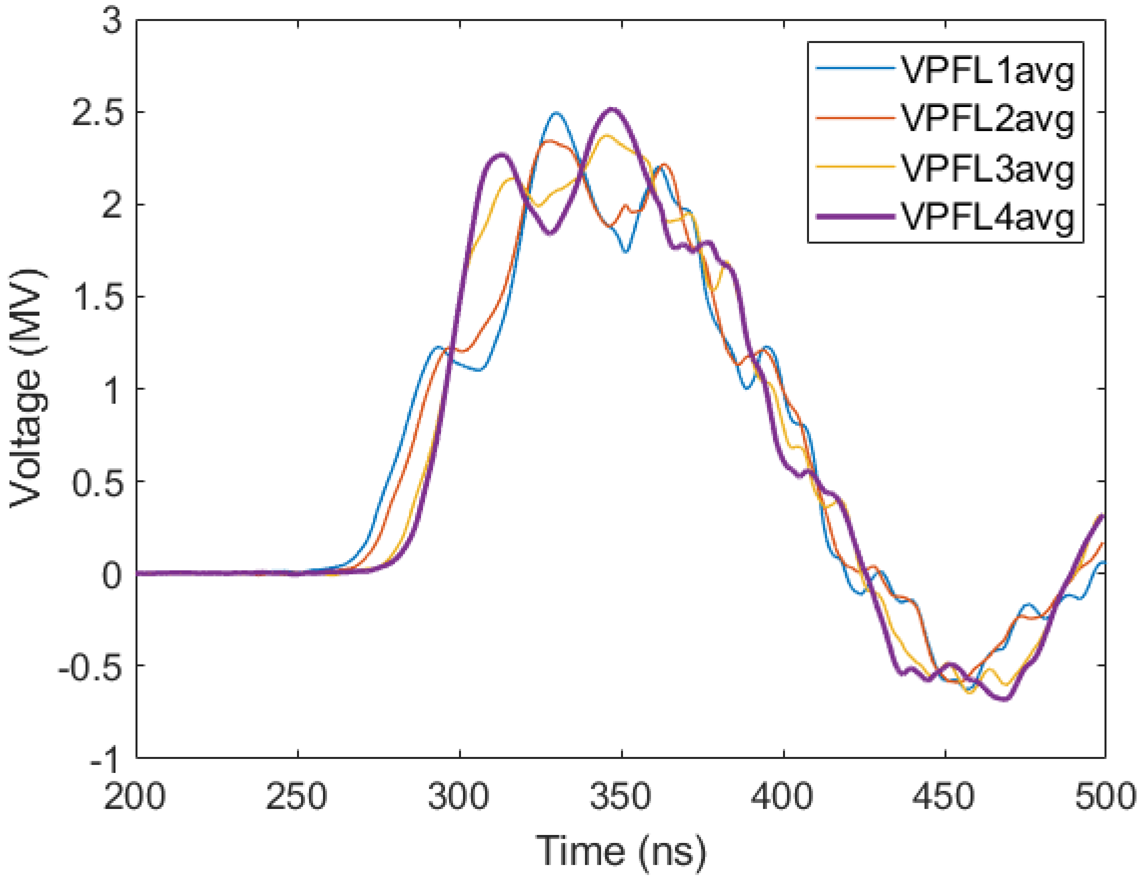




Initial FMA – PFL tests

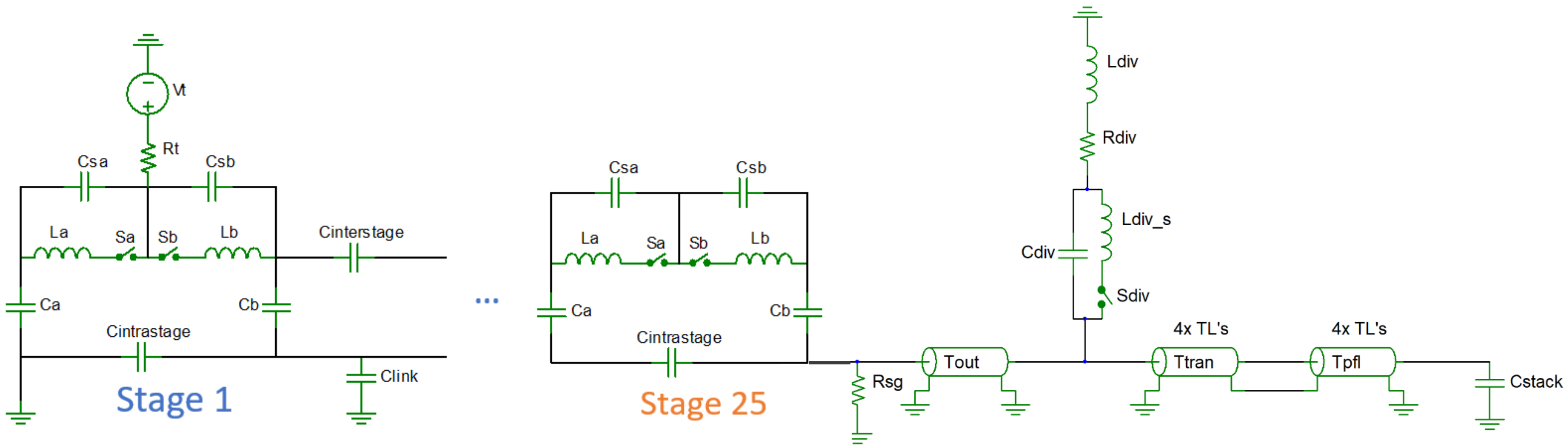
- Verify performance of MTG, Marx, and energy diverters – no vacuum insulator.
- Conducted with up to 50 kV Marx charge voltage
  - Sufficient for continuation of previous insulator tests, up to 2.5 MV applied.

- Length of PFL (~24 ns) is comparable to the Marx output time (~100 ns).
  - Voltage varies along length, risetime sharpens at output end of PFL.



Circuit Modeling of Vulcan

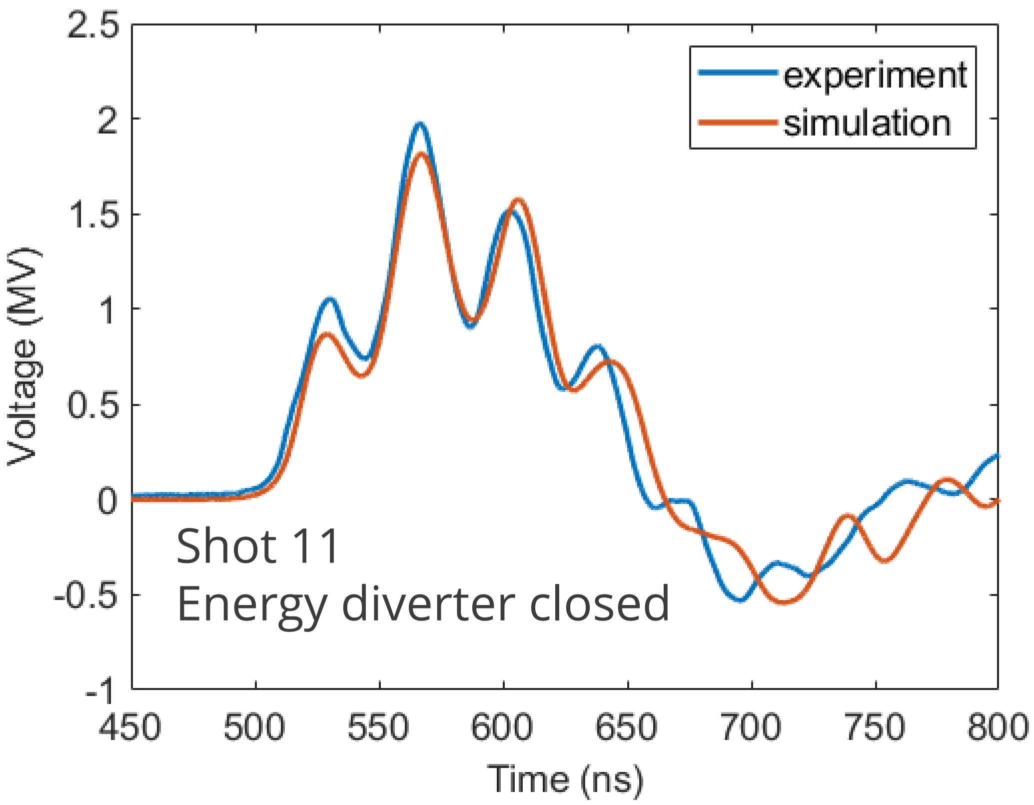
- CASTLE circuit simulator used to model Vulcan*
- Model includes individual Marx stages, stray capacitance between stages, and stage capacitance to ground.
  - Switch r(t) from Martin (voltage or time controlled)
  - Switch timing, stray capacitance important to match experimental waveforms.

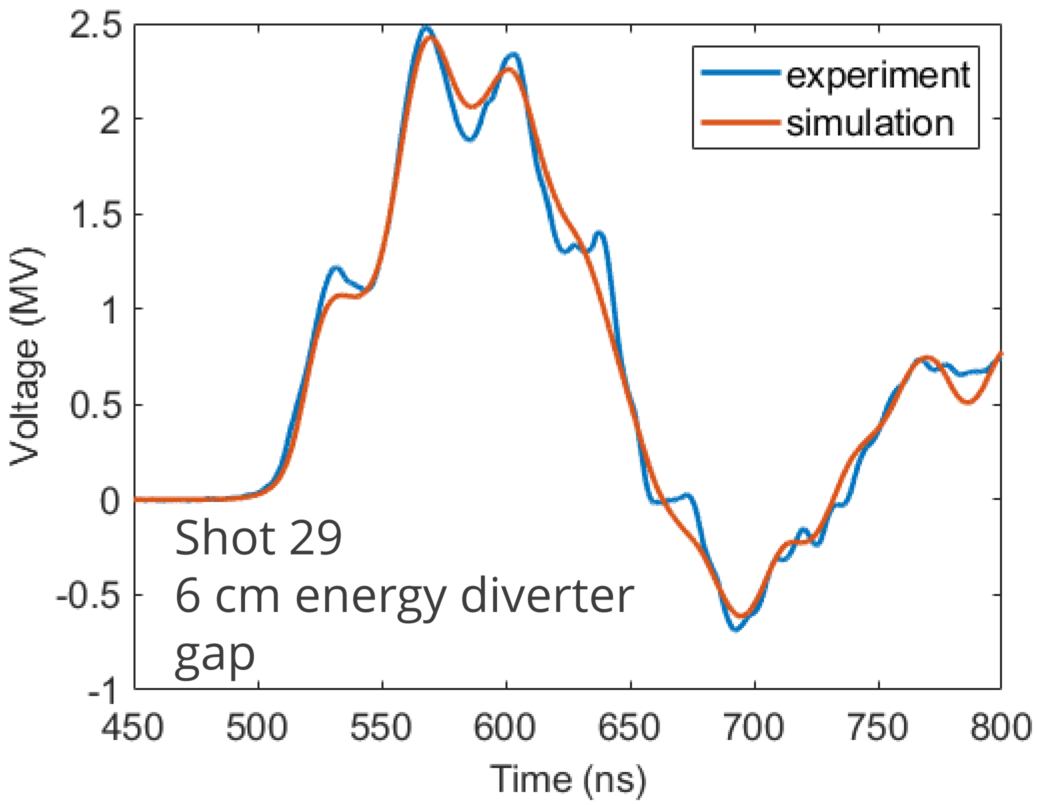


*Poster Session 3 – Ray Allen - Overview of the CASTLE circuit simulator

Circuit models accurately match machine performance

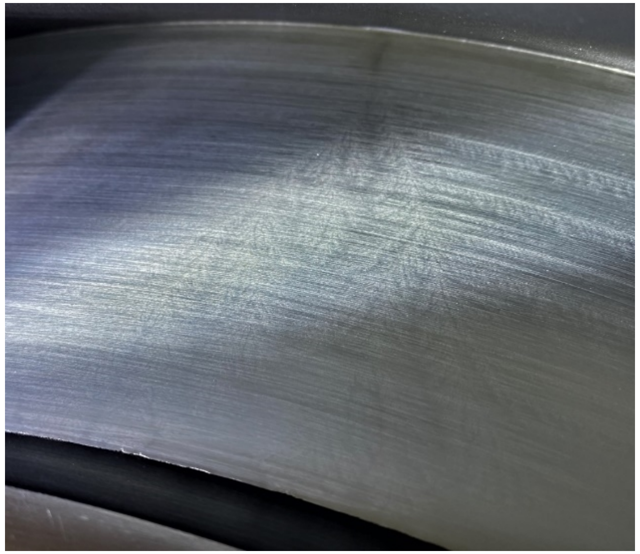
- FMA-PFL Test, no vacuum insulator
- Switch times manually set to match Marx stage voltage measurements

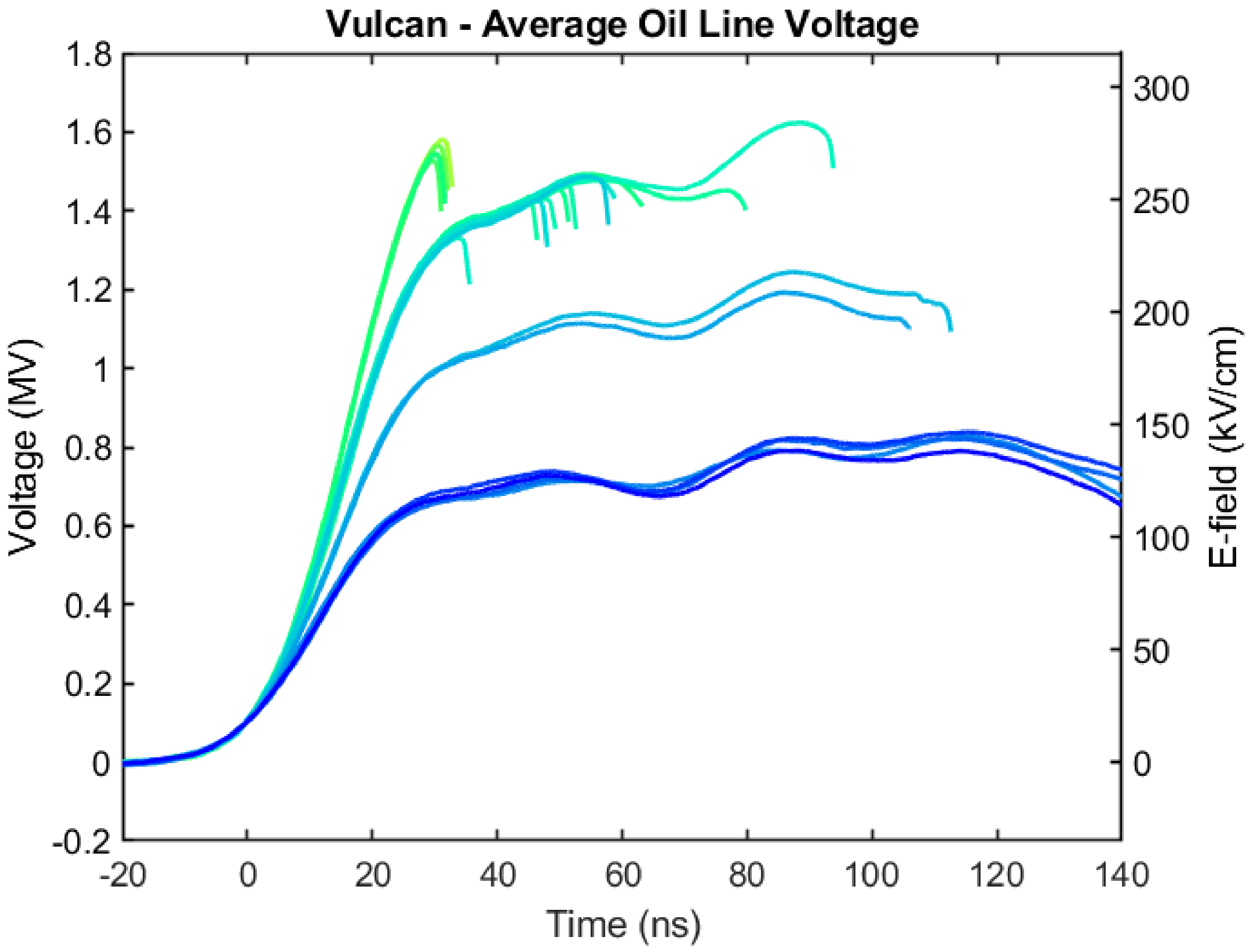




Initial vacuum insulator tests

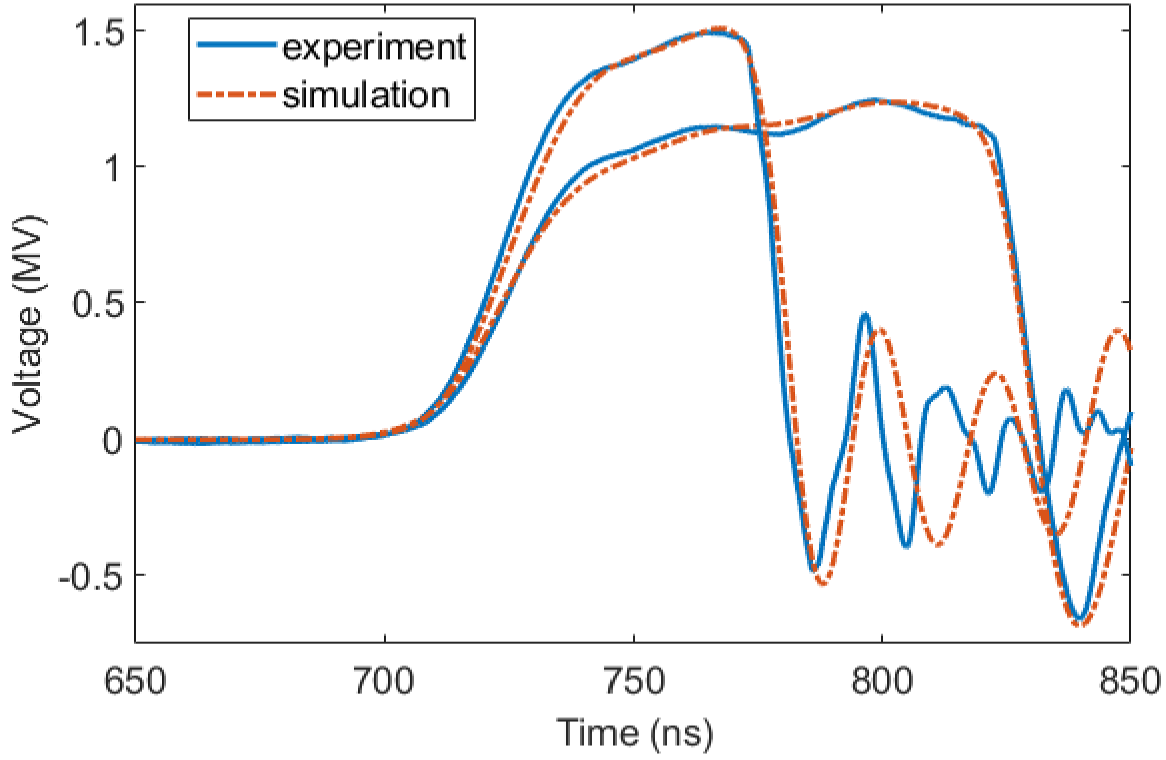
- Initial vacuum insulator tests use a single 2.25” thick 45° Rexolite insulator
- Over 100 experiments completed:
  - Various charge voltages to look at different peak fields and stress times
  - Two insulator samples
  - Refurbishment variations





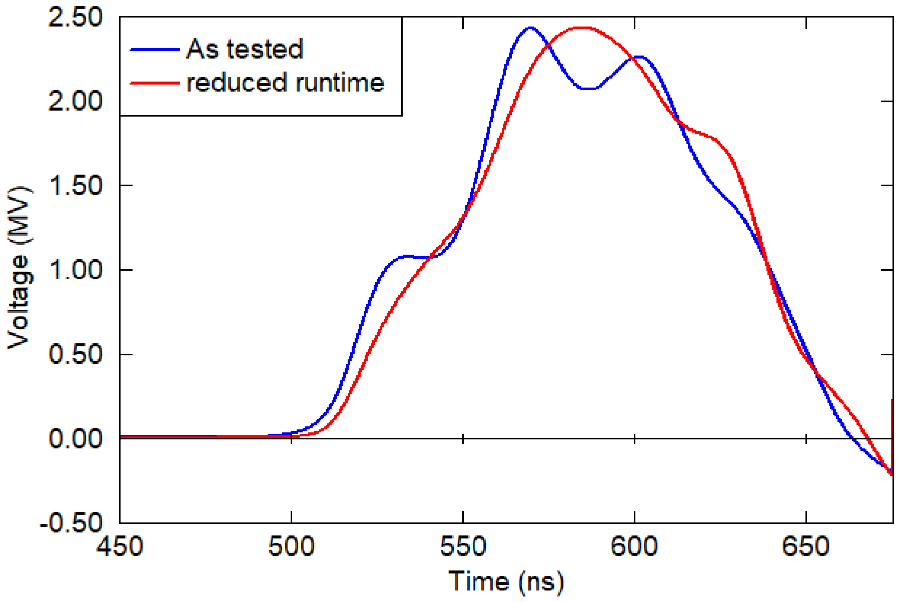
Circuit models match output into insulator stack load

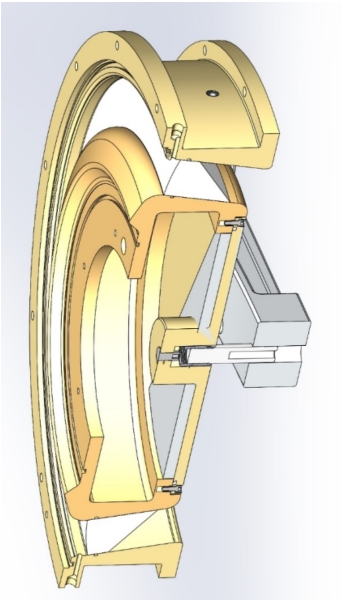
- Single 2.25” thick 45° Rexolite insulator
- Two charge voltages with varied stress time.

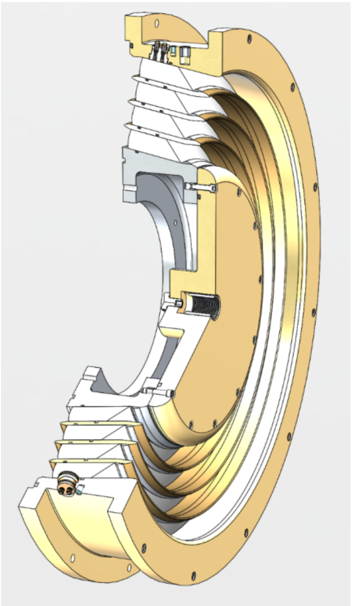


Future Work

- Optimizing FMA triggering.
  - Triggering additional stages, reducing FMA runtime, could smooth output pulse
- Operating FMA at higher charge voltages.
- Conducting experiments with multi-insulator stacks (baseline 45°, variations with anode plugs)







Conclusion

- Vulcan is a new intermediate scale pulsed power facility at Sandia.
  - Vacuum insulator experiments at up to 5 MV
  - Evaluation of Fast Marx technology.
- Performance of the FMA/PFL matched expectations at up to 50 kV Marx charge voltage.
- Over 100 vacuum insulator tests have been completed on a baseline insulator consisting of a single 2.25″ 45° Rexolite insulator.
- Future experiments will be conducted at higher voltage on larger insulator stack assemblies.