Presentation Submission Information:

- Presentation ID#: 3.3
- Presentation Title: Hybrid Breakers
- Author(s): Rajendra Prasad Kandula, Marcio L. Magri Kimpara, Elvey T. Andrade, Jonathan Harter, Marm Dixit
- Organization(s): Oak Ridge National Laboratory



OAK RIDGE National Laboratory

DOE OE TRAC Peer Review 2026

Presentation ID#: 3.3

Hybrid Breakers

Rajendra Prasad Kandula (PI), Marcio Magri Kimpara (Co-PI), Elvey T. Andrade, Jonathan Harter, Marm Dixit

U.S. DEPARTMENT OF ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

Project Overview

U.S. DEPARTMENT of ENERGY

- Project Description: Develop a medium voltage (5-10 kV) hybrid circuit breaker technology for implementing fast protection (< 1 ms) in DC/AC systems
- Period of Performance: 10/01/2025 to 09/30/2027
- Award Amount: $1,200,000
- Prime Awardee: Oak Ridge National Laboratory
- Partners: NA
- Technology Area: DC Circuit Breakers
- Alignment/Supports Strategic Pathway: Grow

  Proposed hybrid breaker will provide faster protection that will enable growth of medium voltage DC (MVDC) systems

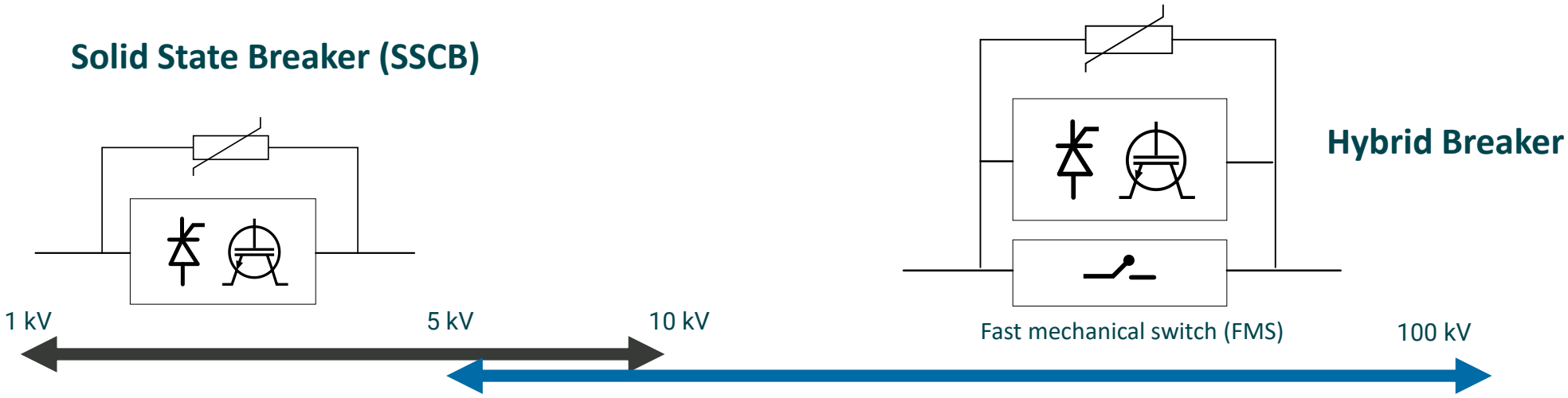
Problem Statement

U.S. DEPARTMENT of ENERGY

- The growing penetration of direct current (DC) sources and DC loads is driving increased interest in medium-voltage direct current (MVDC) distribution systems.
- Unlike alternating current (AC) systems, DC systems lack a natural current zero crossing, and fault currents increase much more rapidly (lower network impedance) making protection significantly more challenging.
- Hybrid circuit breaker is a key enabling technology for practical MVDC systems

Application: MVDC distribution, data centers, utility scale storage, AC side protection for medium voltage AC (MVAC) converters

Why Hybrid?



- ✓ SSCBs operate very quickly (typically within 10 to 100 microseconds)
- ✓ Arc-less operation
- X At MV levels, semiconductor devices must be connected in series to withstand high voltages
  - Increases cost and complexity
  - Introduces significant steady-state conduction losses

Hybrid Breaker: A combination of solid-state switch and fast mechanical switch (FMS)

- FMS based on Thomson coil is expected to operate within 1 mS
  - Note: Traditional mechanical breakers operate within 10-40 ms
- Solid state switch based on Thyristor
- Energy absorption using metal oxide varistor (MOV)

Technical Approach

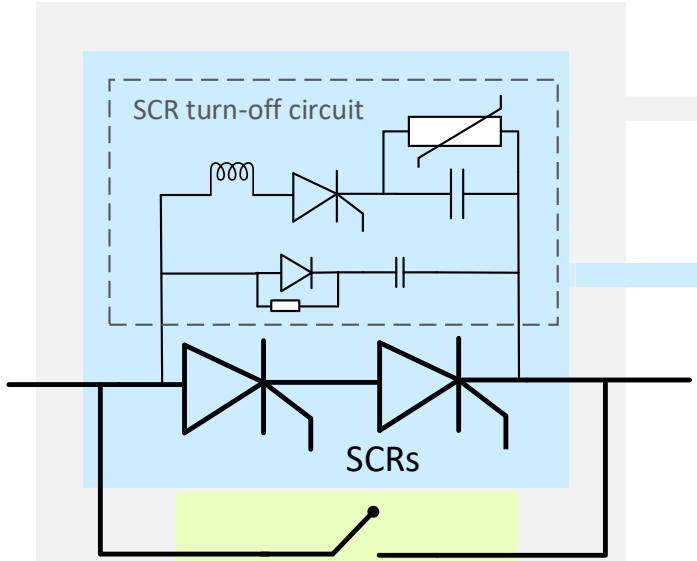
Task 1. Project Management

G/NG

G/NG

FY2026

FY2027



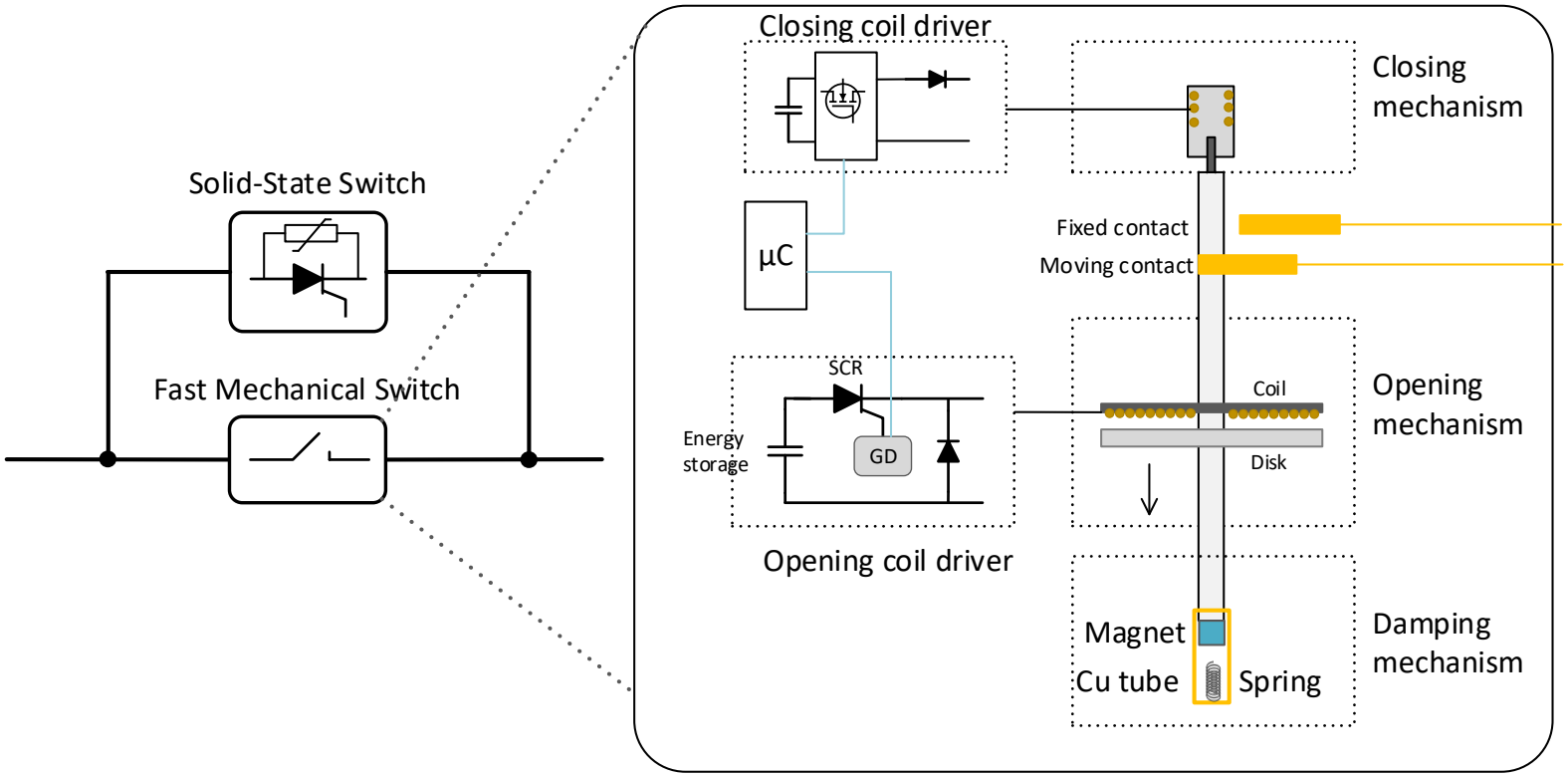
Task 4. Integrated Switch Development

Task 3. Silicon Controlled Rectifier (SCR) based Solid State Switch (SSS) Development

Task 2. Fast Mechanical Switch (FMS) Development

Fast Mechanical Switch Development

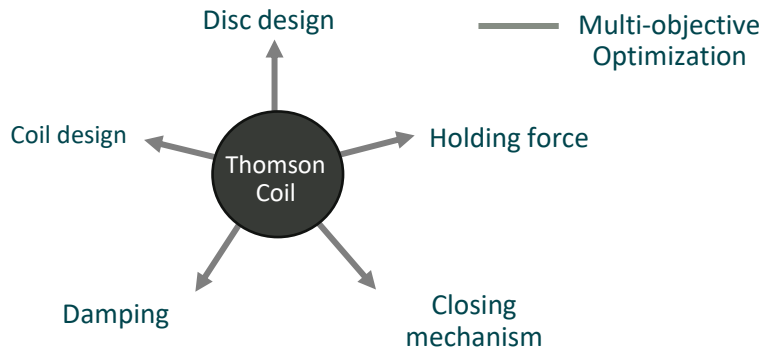
The critical element of hybrid breaker is the FMS that needs to operate in 1 millisecond to be effective in DC systems



Various components of Fast Mechanical Switch based on Thomson coil

- Electromagnetic actuation systems are faster compared to hydraulic, pneumatic, or spring-loaded actuation mechanisms
- Small stroke is a drawback for piezoelectric and magnetostrictive devices
- Thomson coils based on electromagnetic repulsion are widely used because of smaller opening time
- Multiple Thomson coil-based hybrid circuit breakers have been proposed in literature
- Team will try to improve on multiple parameters to further reduce closing time

Design parameters for Thomson coil



Design of Coil and Driver For FMS

Goal: Separate contacts by 5 mm within 0.5 ms

The energy required for disc displacement was determined using fundamental physics principles

Design Flow

- Calculate velocity, acceleration
- Required force (estimated mass):

$$F_{reqd} = m * acc_{disc}$$

- Calculate coil current to generate necessary force

$$F_{reqd} = F_{disc} = I_{coil} * I_{disc} * \frac{dM}{dx}$$

$$I_{disc} = k * I_{coil} * N_{coil}$$

$$where\ k, \frac{dM}{dx} = f(\rho_{disc}, D_{disc}, t_{disc}, dx, D_{coil})$$

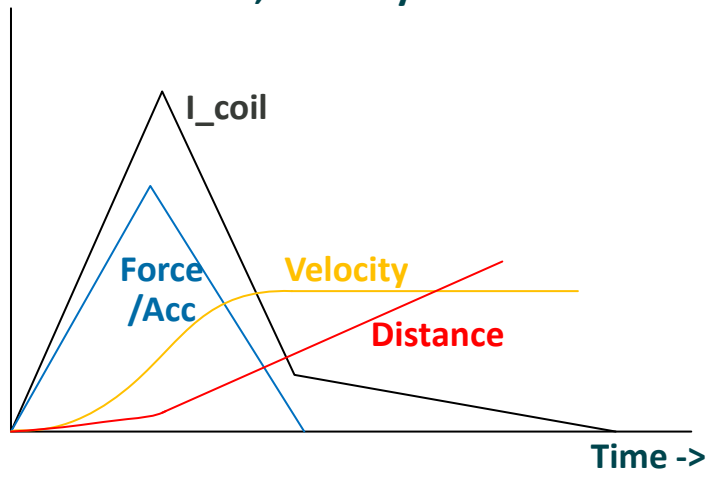
Initial design only I_{coil} is varied and others are fixed

- Opening coil driver design

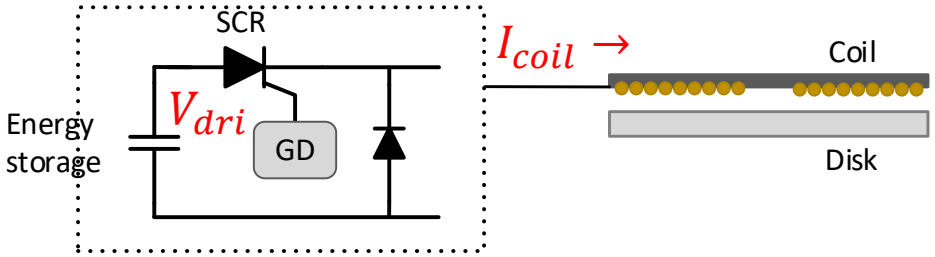
$$V_{dri}^2 * C_{dri} = I_{coil}^2 * L_{coil}$$

$$t_{open} \cong 0.5\pi\sqrt{C_{dri} * L_{coil}}$$

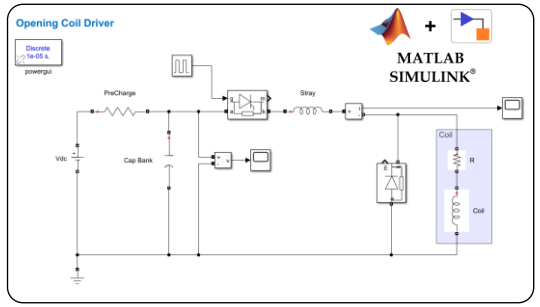
Conceptual current, force, acceleration, velocity and distance



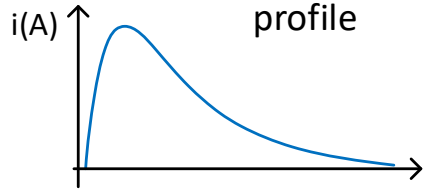
Schematic of Opening Mechanism



Design Verification of Coil and Driver

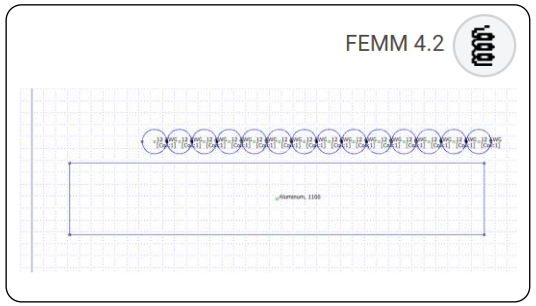


Coil + Driver Simulation



Excitation

Design Parameters

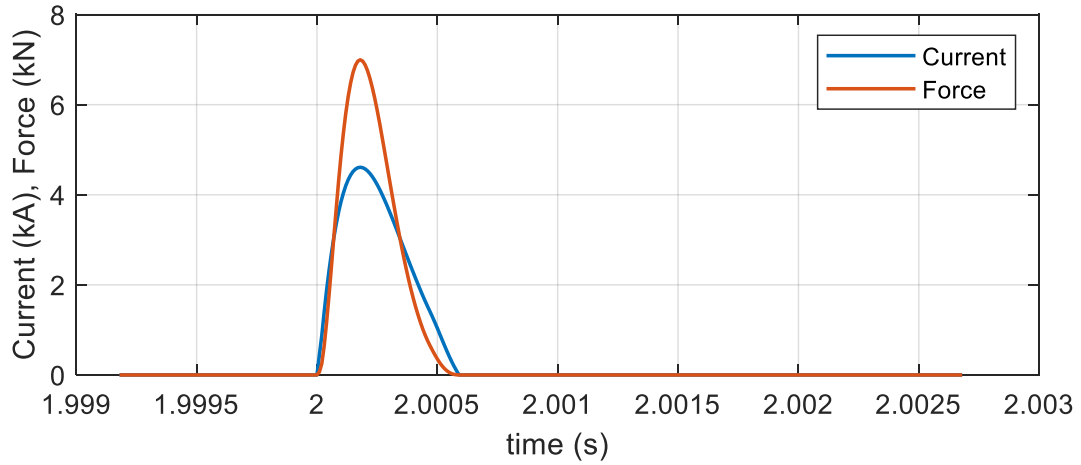


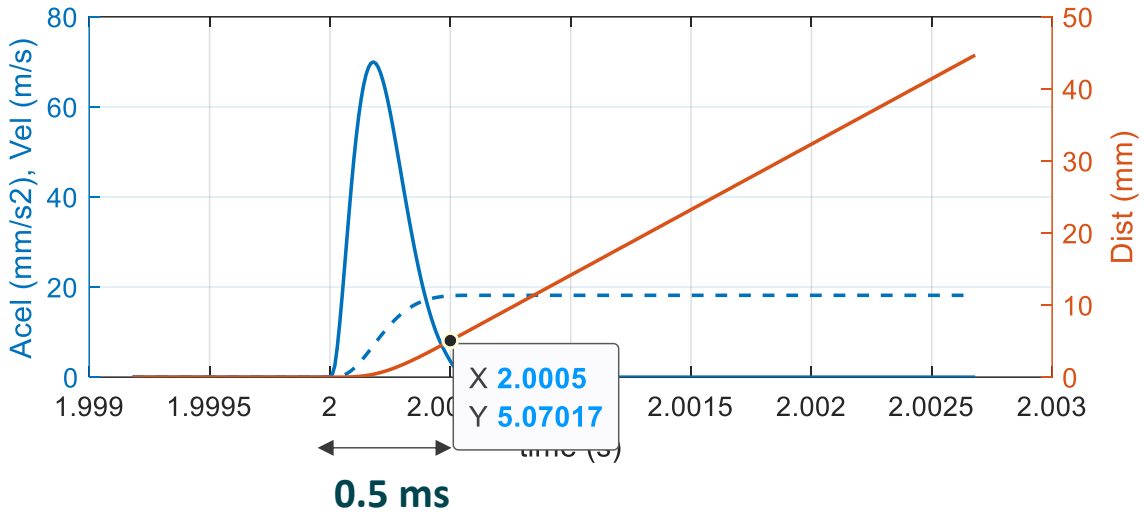
Force

2D Axisymmetric FEM Model

Co-simulation to verify the operation of driver, coil, and disc

Finite Element Method (FEM)/Matlab Results

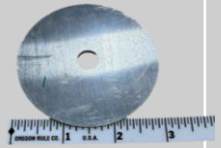


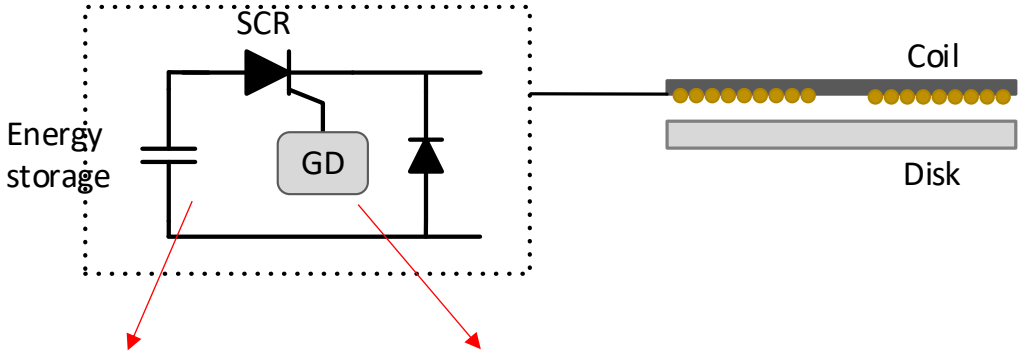


0.5 ms

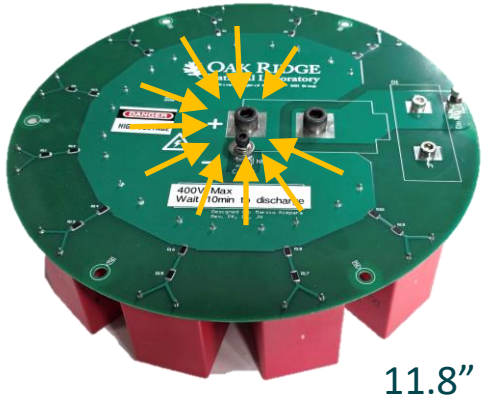
Build of Coil and Driver For FMS

- Capacitor bank to provide pulse energy for the opening coil is designed and built
  - Challenge: Current (5 kA) sharing between capacitors
- SCR gate driver is built and tested
  - Optical inputs
  - High gate drive current to enable SCR to handle 5 kA

		Parameter	Value
	Disc	Thickness	3 mm
		Material	Aluminum
		OD	76.2 mm
	Coil	OD	77.2 mm
		ID	11.65 mm
		Turns	19
		Wire	14 AWG
		Inductance	4.48 uH
	Driver	Capacitance	4 mF
		Voltage	380 V



Capacitor bank + SCR



11.8” (OD), 2.6” (H)

SCR gate driver



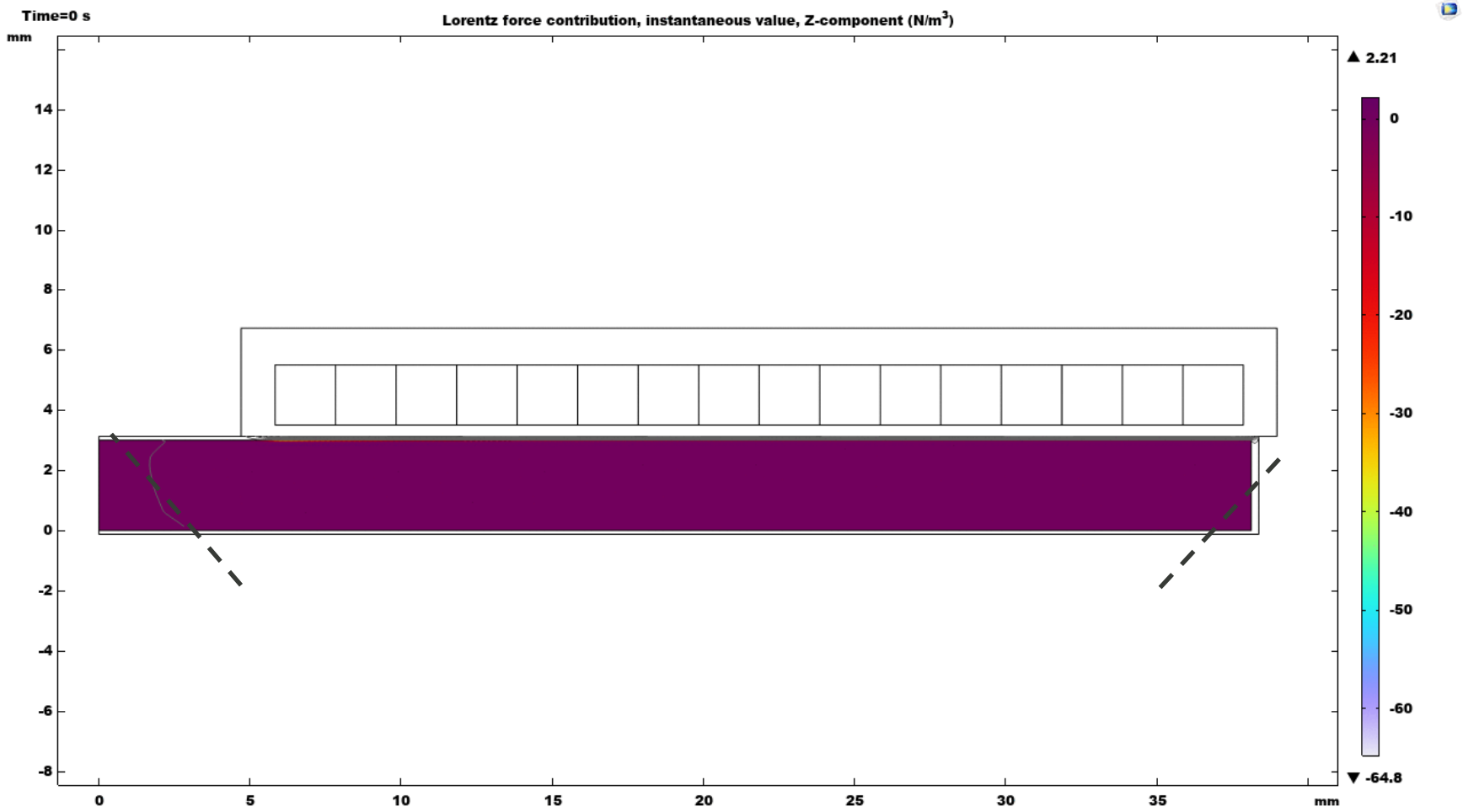
Component	Part Number	Specs
Capacitor (x10)	DCP4G064009JD4KSSD	400uF, 400V
SCR	TZ600N16KOFHPSA1	1600V, 17kA, 200A/us
Diode	MEO450-12DA	1200V, 4.8kA

Armature Optimization



- Thickness optimized based on the eddy-currents penetration
- Corner chamfers can be implemented and will be incorporated in subsequent design iterations

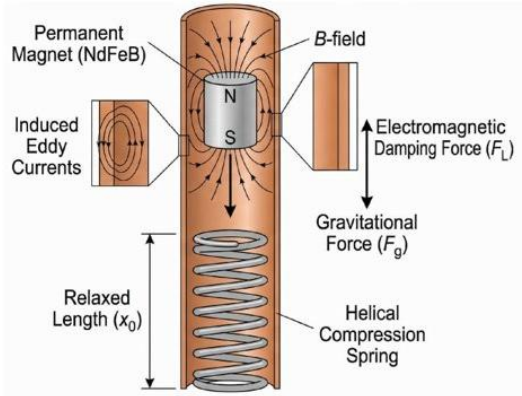
COMSOL simulation



Damping Mechanism Concept

- The high kinetic energy imparted by the Thomson coil actuator (TCA) requires an equally high-performance braking system to prevent mechanical failure and contact rebound
- Eddy current damping (electromagnetic brake) adopted
- Permanent magnet moving in a copper rod will generate eddy currents, which in turn will oppose the magnet motion
- FEM simulations conducted to analyze
  - Size and shape of permanent magnet
  - Thickness of copper rod
  - Need for a spring

Eddy currents induced in copper tube walls

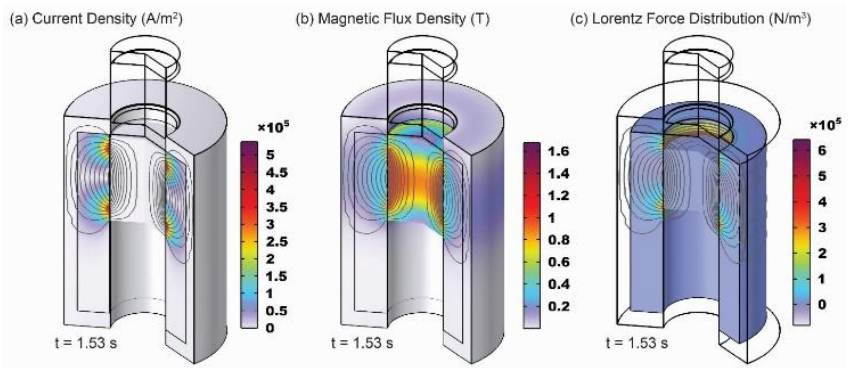


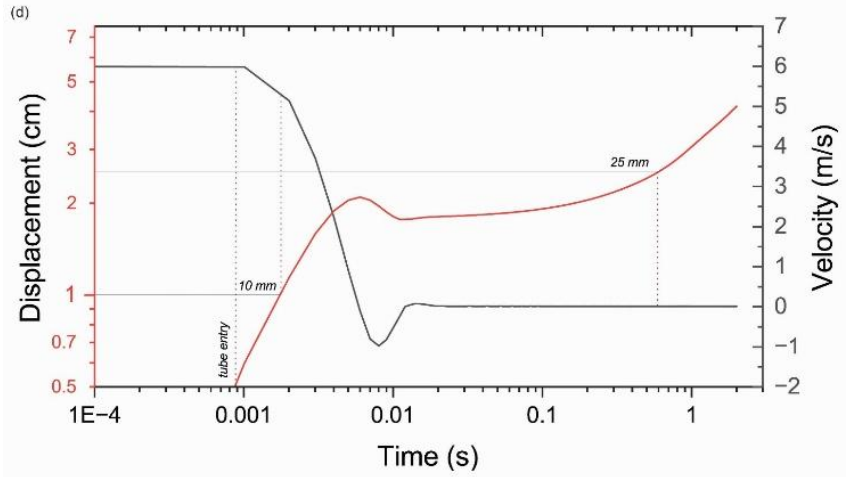


Electromagnetic Braking

Simulation

(a) Spatial distribution of induced current density, (b) magnetic flux density, and (c) Lorentz force density at t = 1.53 s in the simulation frame.





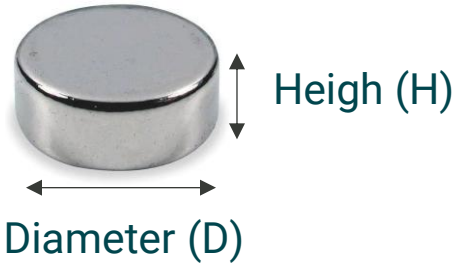
Dynamic response of the armature. The dashed lines highlight the tube entry point and the transition from transient braking to steady-state descent

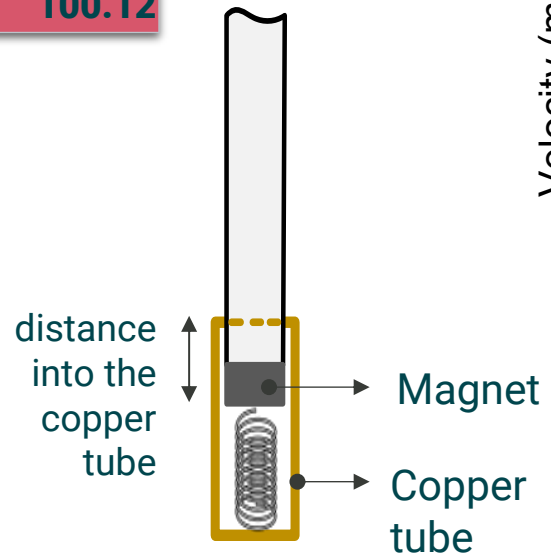
Magnet Geometry Optimization

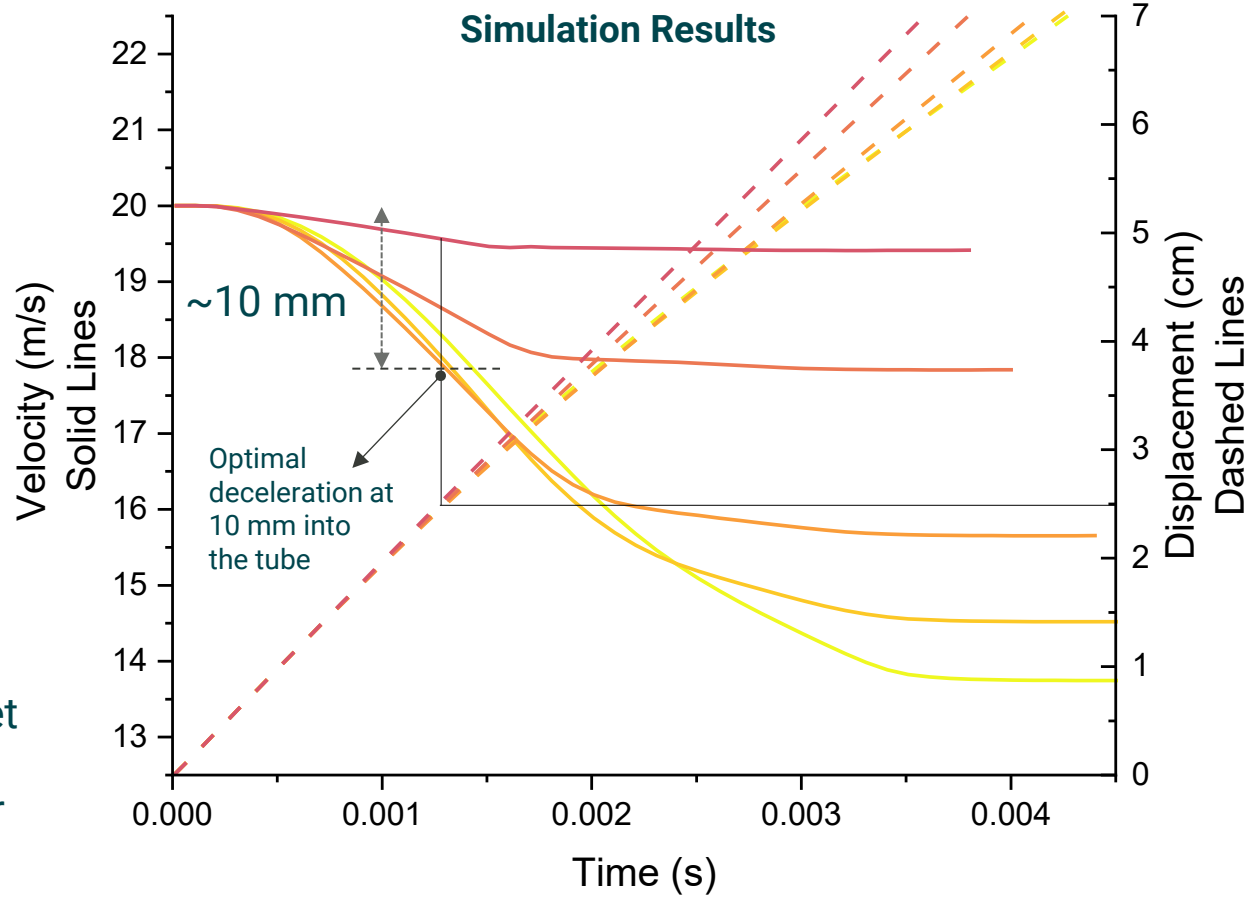
U.S. DEPARTMENT of ENERGY

Optimal

H (inch)	D (inch)	M (g)
1	1	100.26
0.75	1.2	100.14
0.5	1.4	100.12
0.25	2.0	100.06
0.125	2.9	100.12

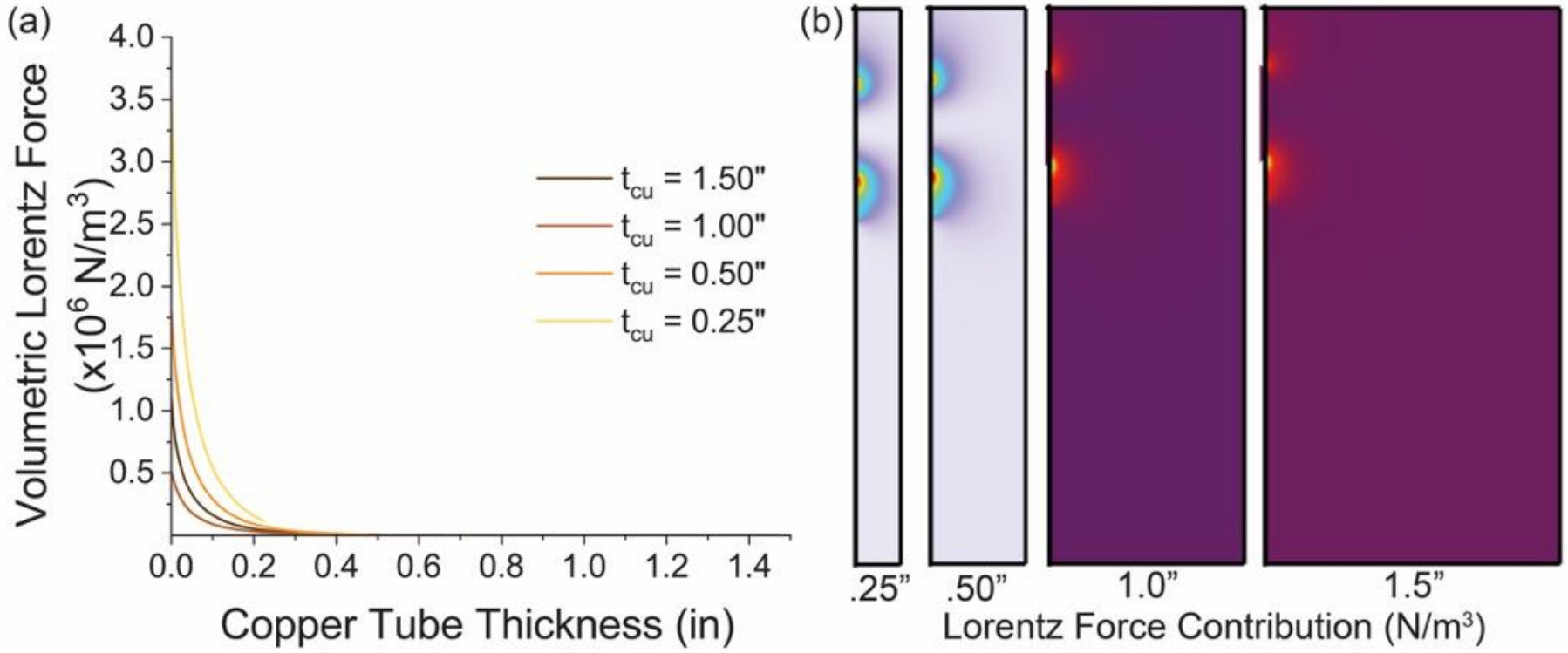






Magnet shape optimized to maximize deceleration occurring within 10 mm of entry into the tube

Copper Tube Thickness Optimization

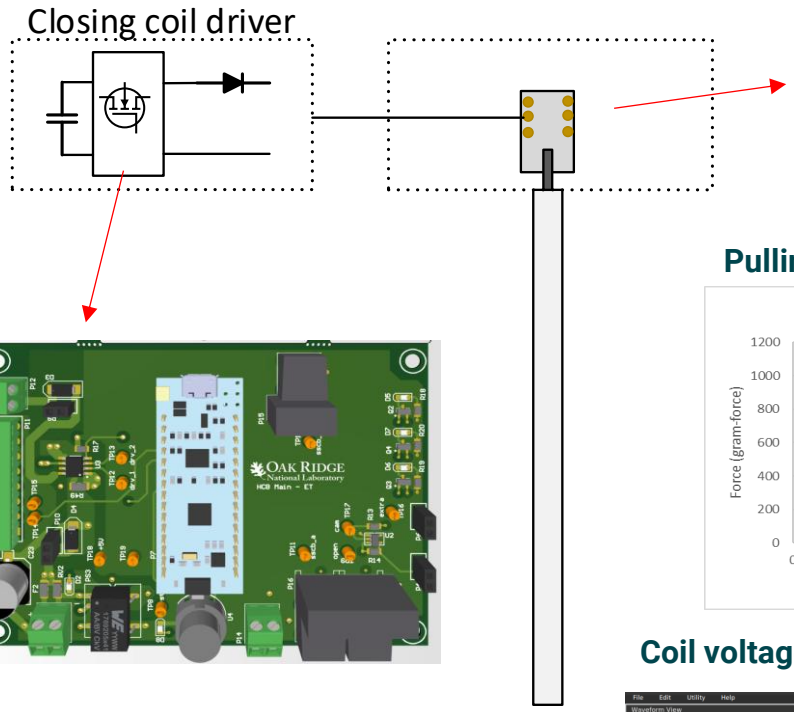




Copper tube wall thickness optimized based on the eddy-current penetration

Design of Closing Mechanism

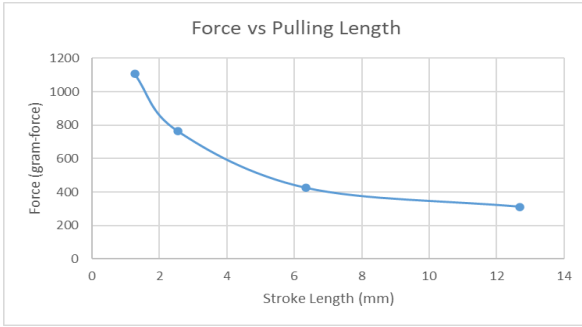
- Push-pull solenoid selected to implement the closing coil
  - Ease of mechanical integration
- Closing coil driver
  - PWM technique to generate high closing force but low holding force
- Closing time: 5 ms



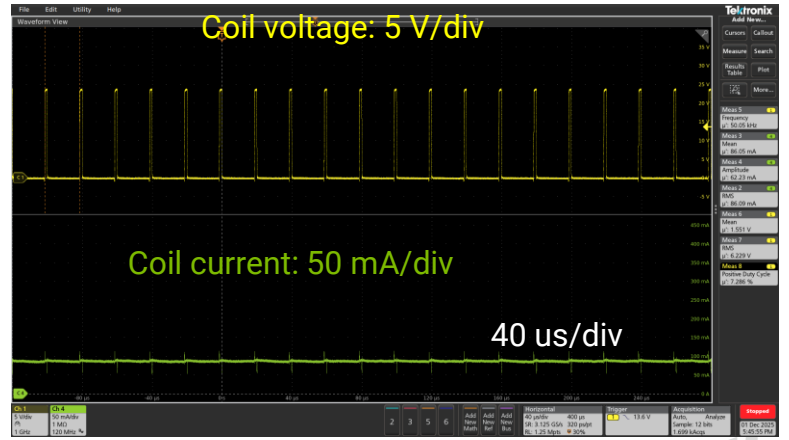


Controller + closing coil driver printed circuit board (PCB)

Pulling force at different stroke length.



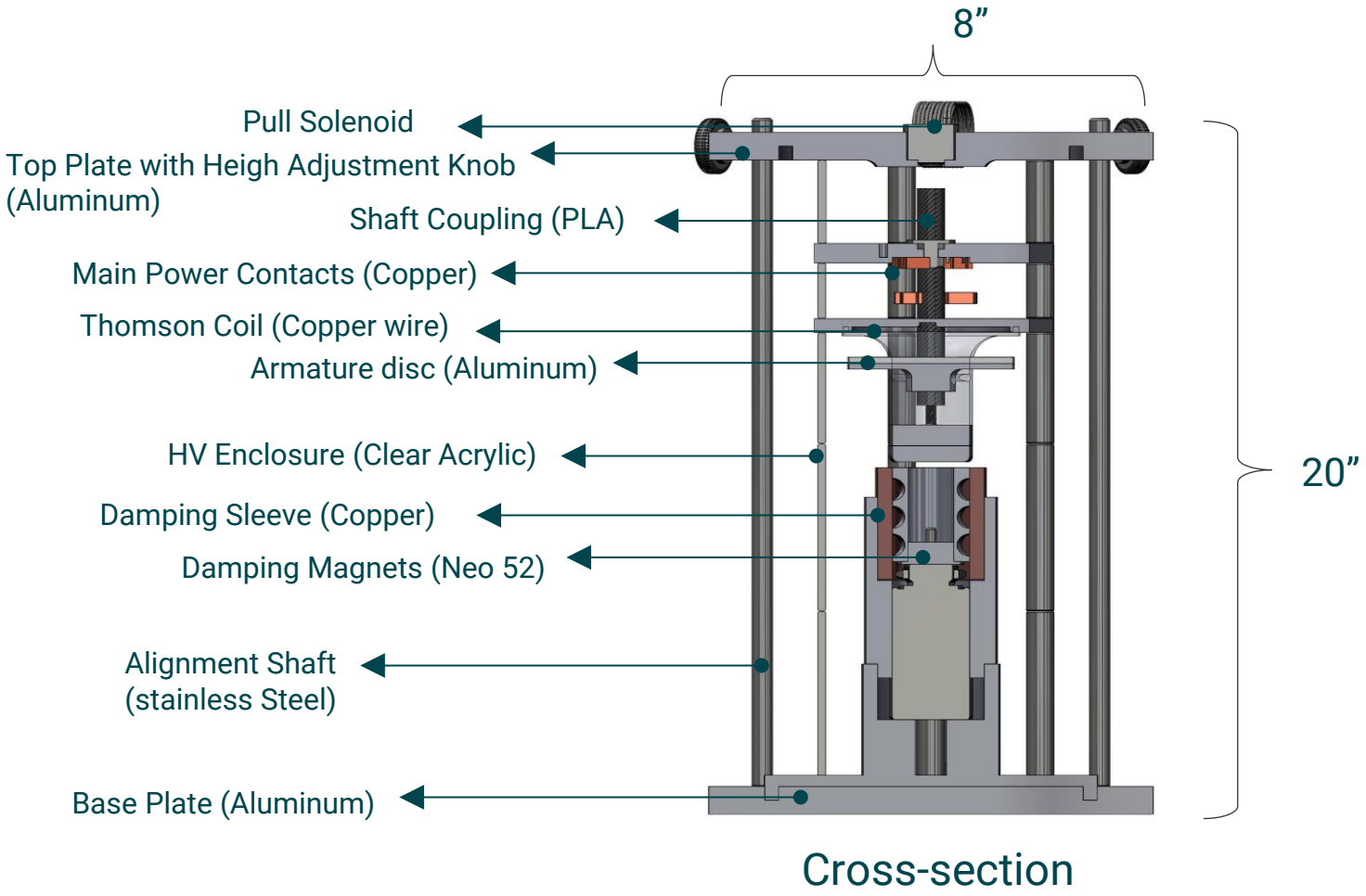
Coil voltage and current applied to coil to hold 281 g



The aim is to minimize the holding force that counteracts the disc opening force

Build of the 5 kV, 100 A FMS

Computer-Aided Design (CAD) including components details of 5kV, 100A fast mechanical switch



Cross-section

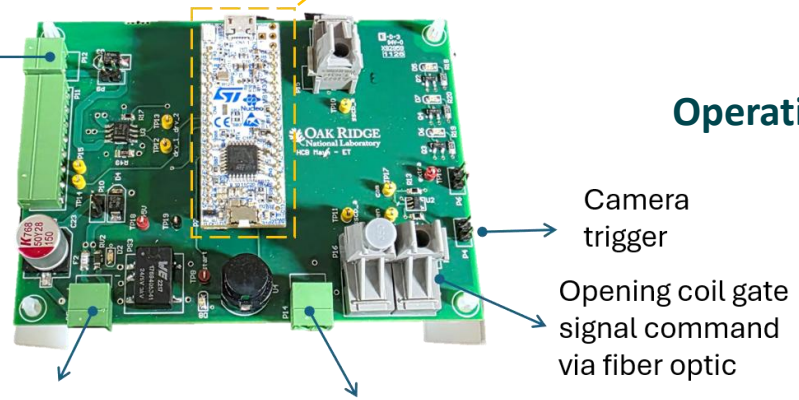
Built prototype of 5kV, 100A fast mechanical switch



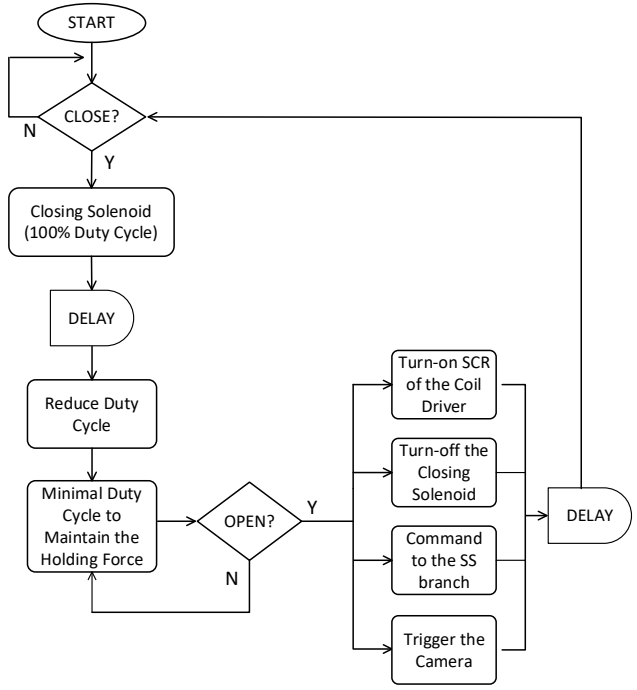
Testing of the first FMS prototype

U.S. DEPARTMENT of ENERGY

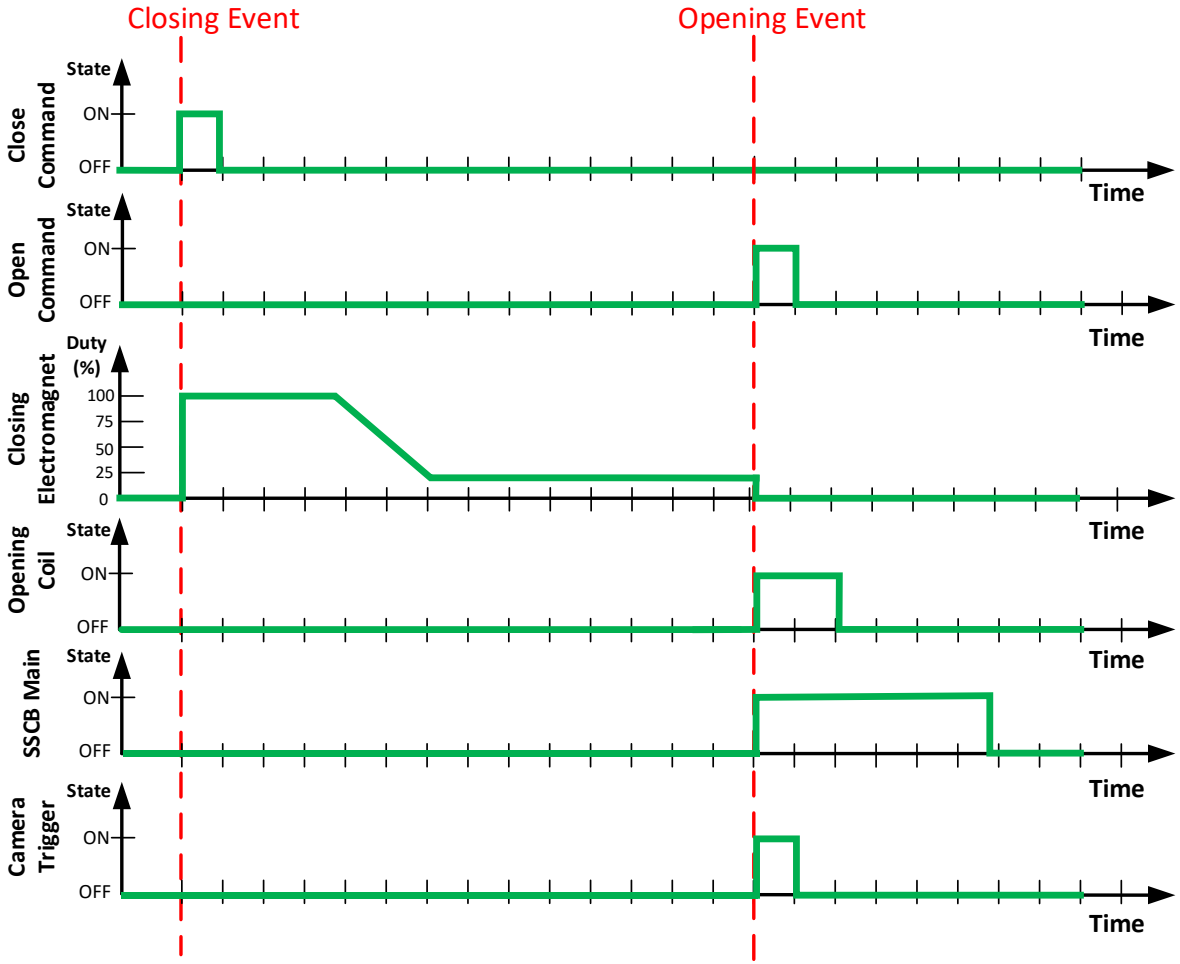
Microcontroller interface board



Operation flowchart

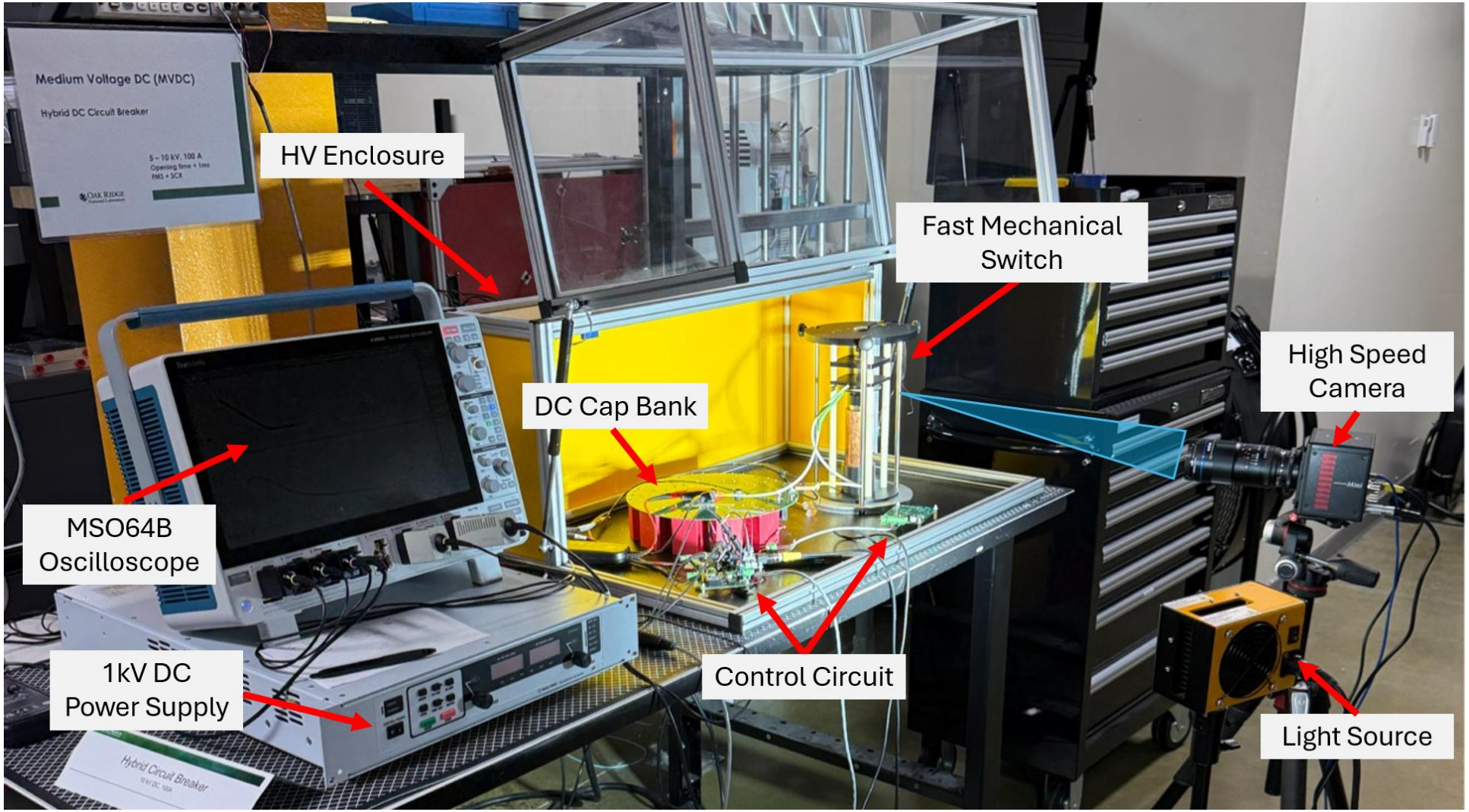


Timing Sequence



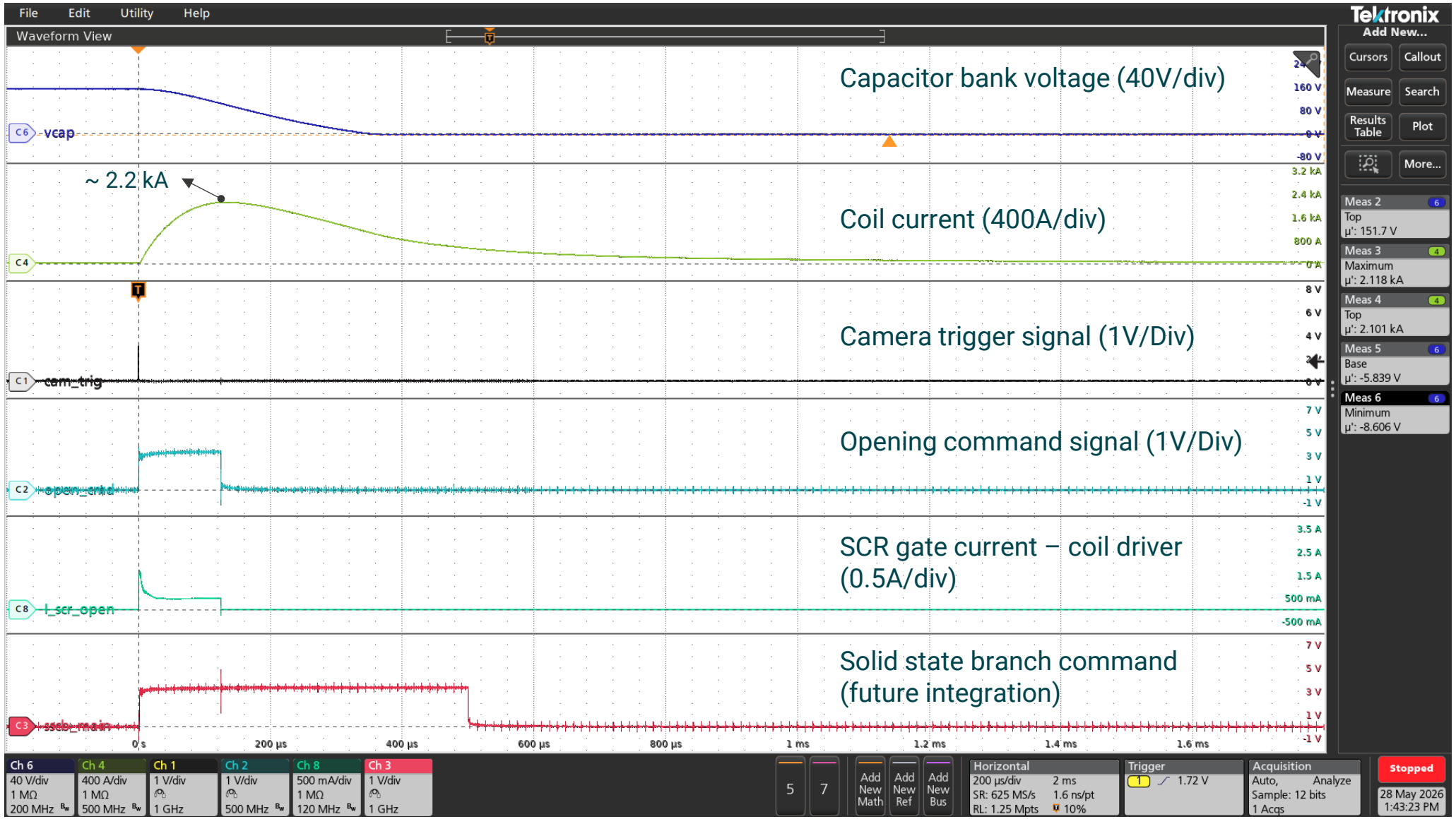
OAK RIDGE National Laboratory

Testing of the first FMS prototype….Contd



Testing setup

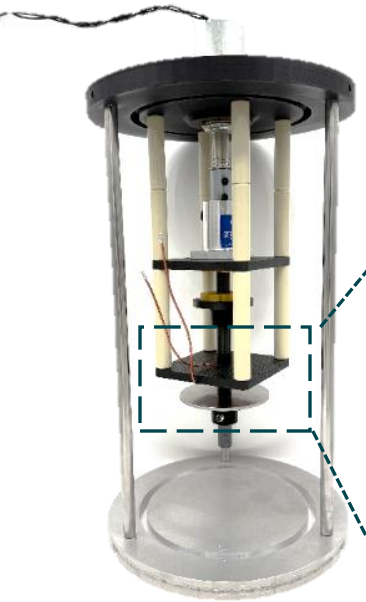
Experimental Results



Oscilloscope screenshot showing the main waveforms for a 150V test (applied to the coil driver)

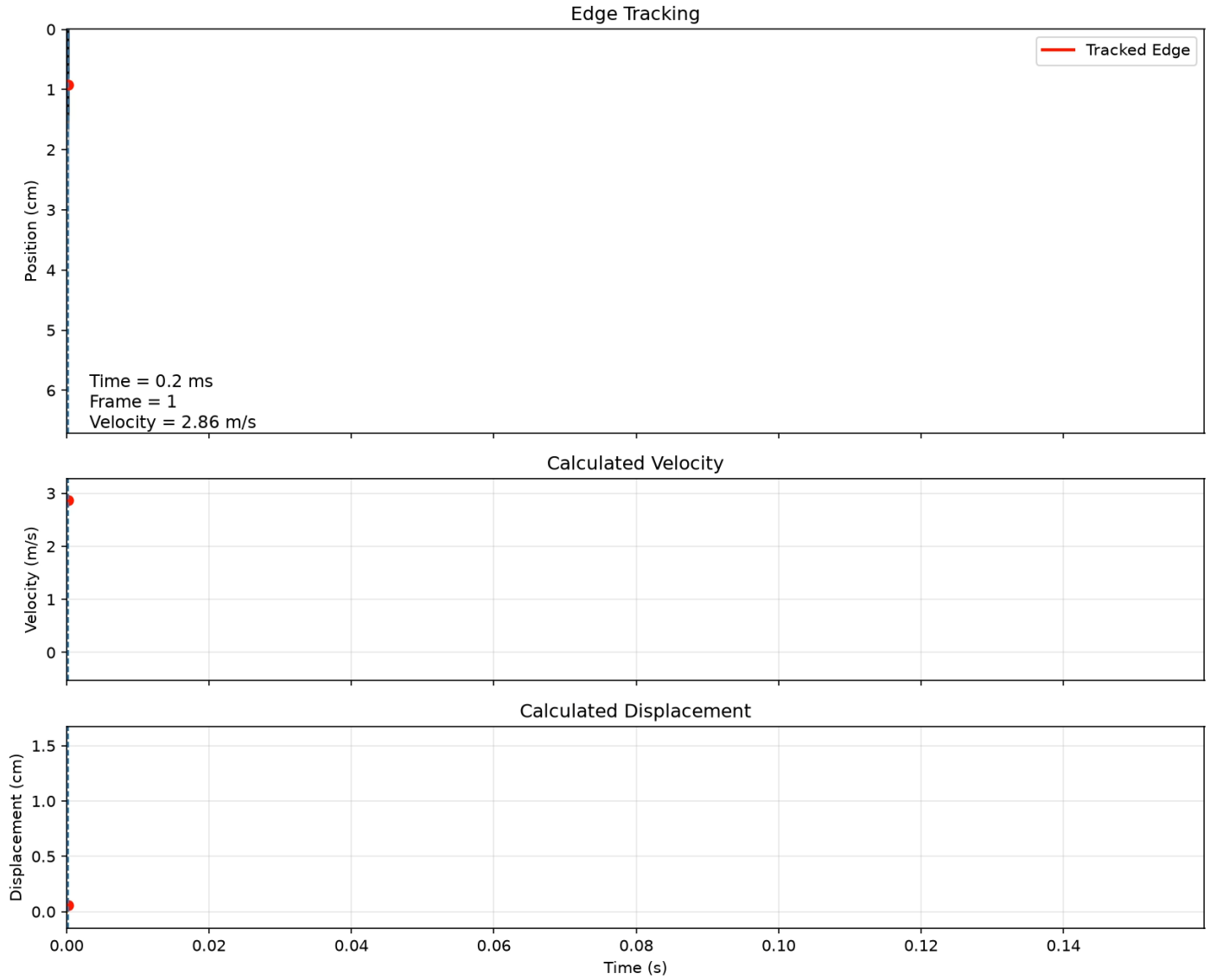
High-Speed Capture of Breaker Operation

U.S. DEPARTMENT of ENERGY



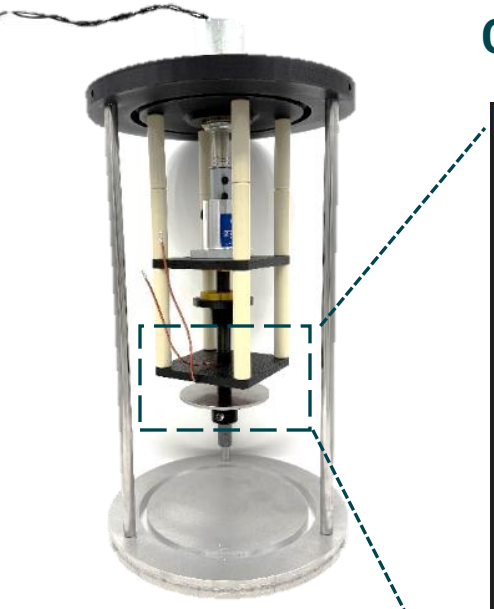
Operating Voltage: 150 V
Capture Frame Rate: 5000 fps



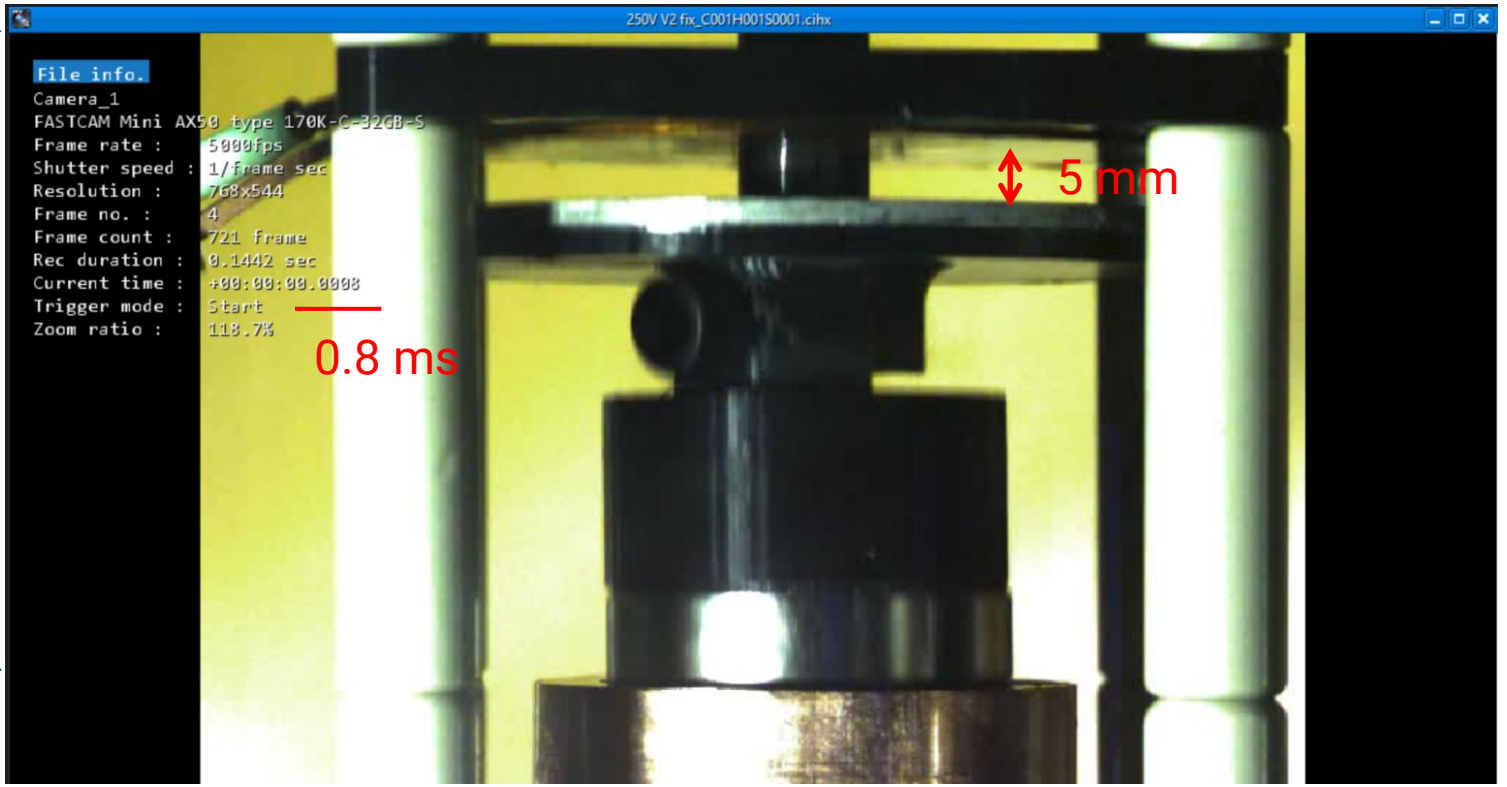


OAK RIDGE National Laboratory

High-Speed Capture of Breaker Operation…Contd

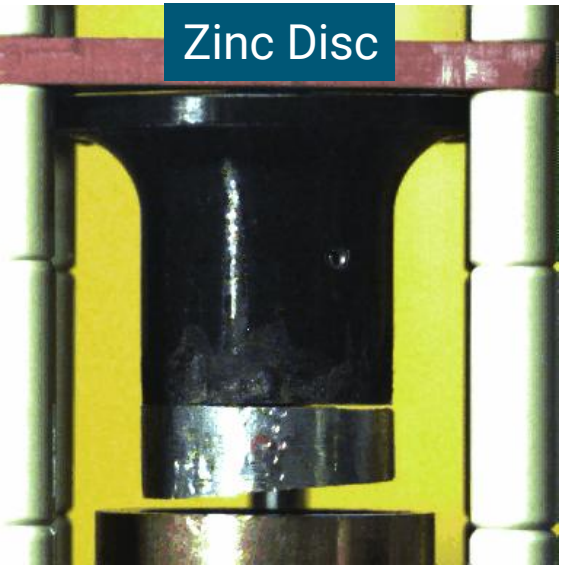


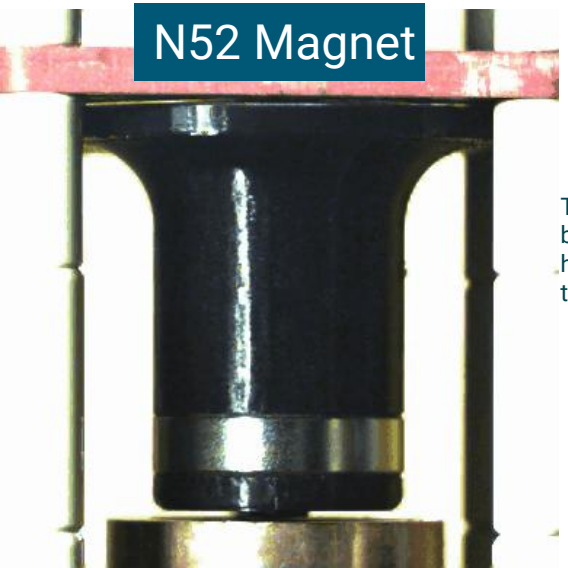
Operating Voltage: 200 V
Capture Frame Rate: 5000 fps

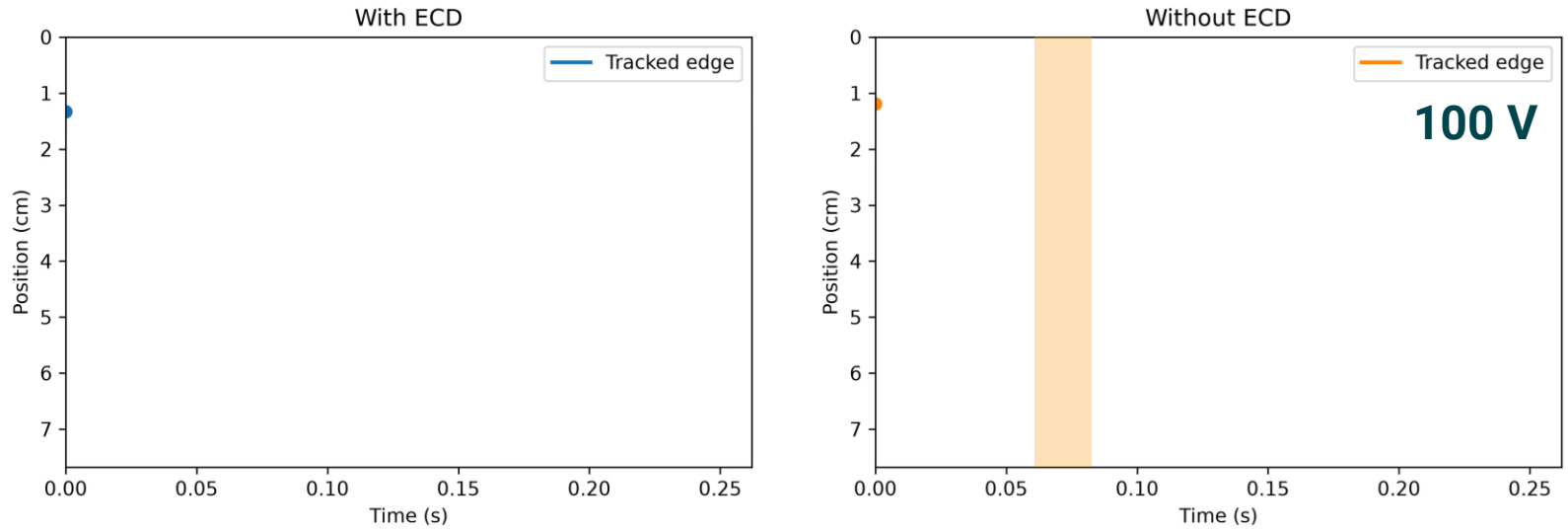


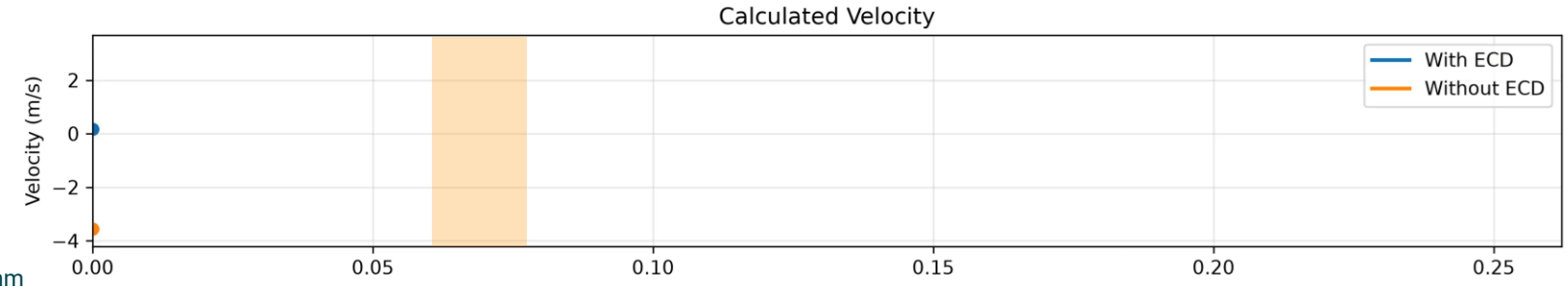
Operation of Hybrid Breaker w/ and w/out Eddy Current Damping (Magnet/ Zinc) for identical mass armature

U.S. DEPARTMENT of ENERGY

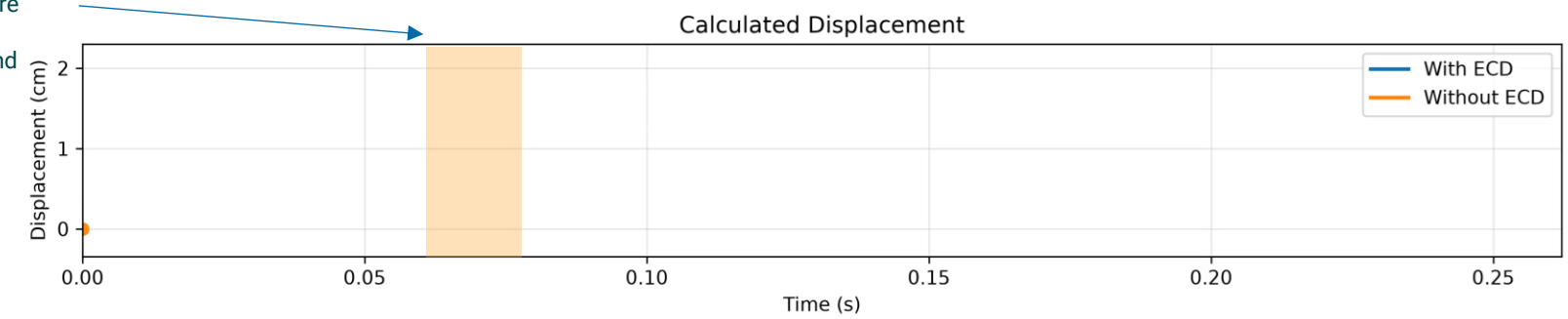








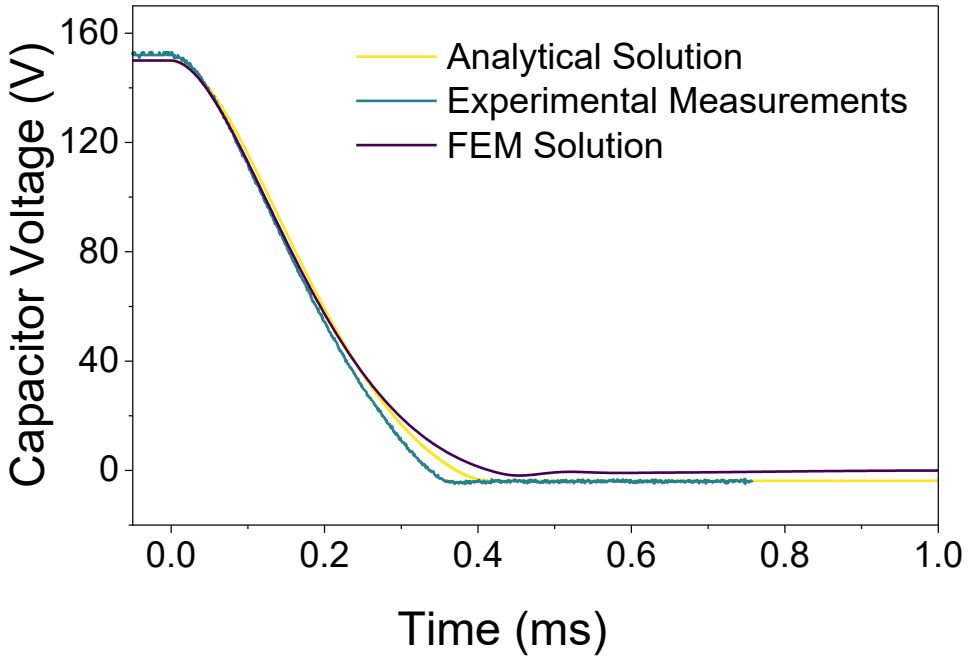
Tracking algorithm breaks as armature hits the coil on rebound

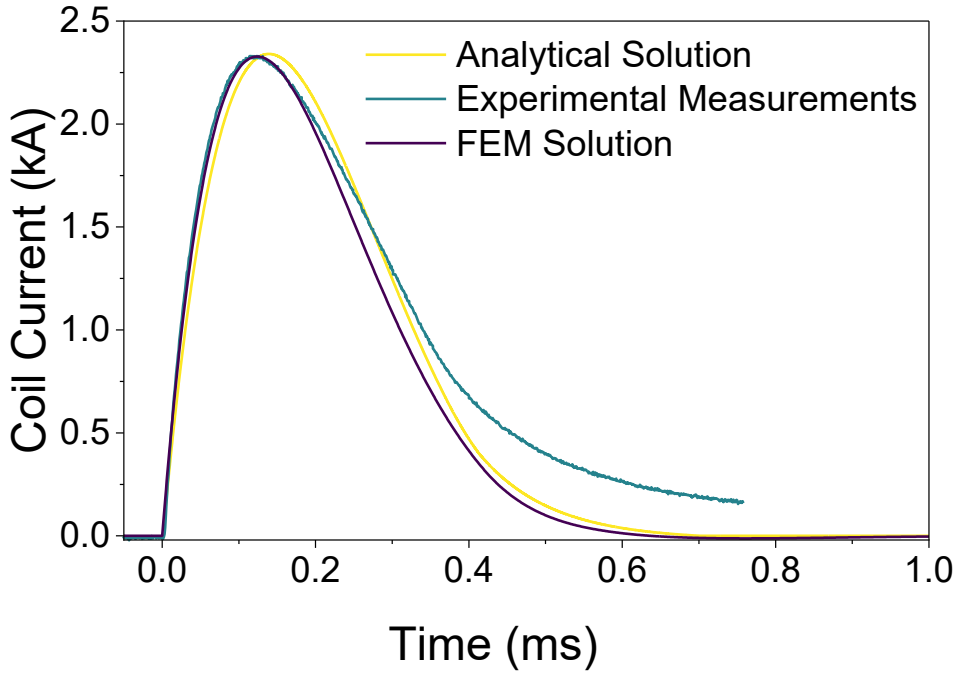


Results Analysis

- Comparison of Experimental Data with Analytical and FEM Model

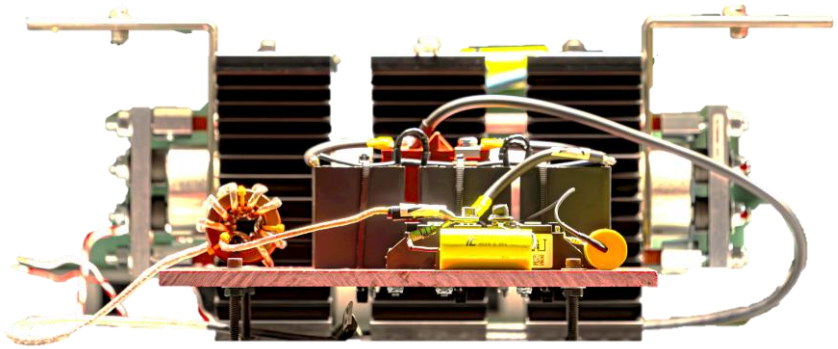
Testing condition: 150V





Solid State Switch

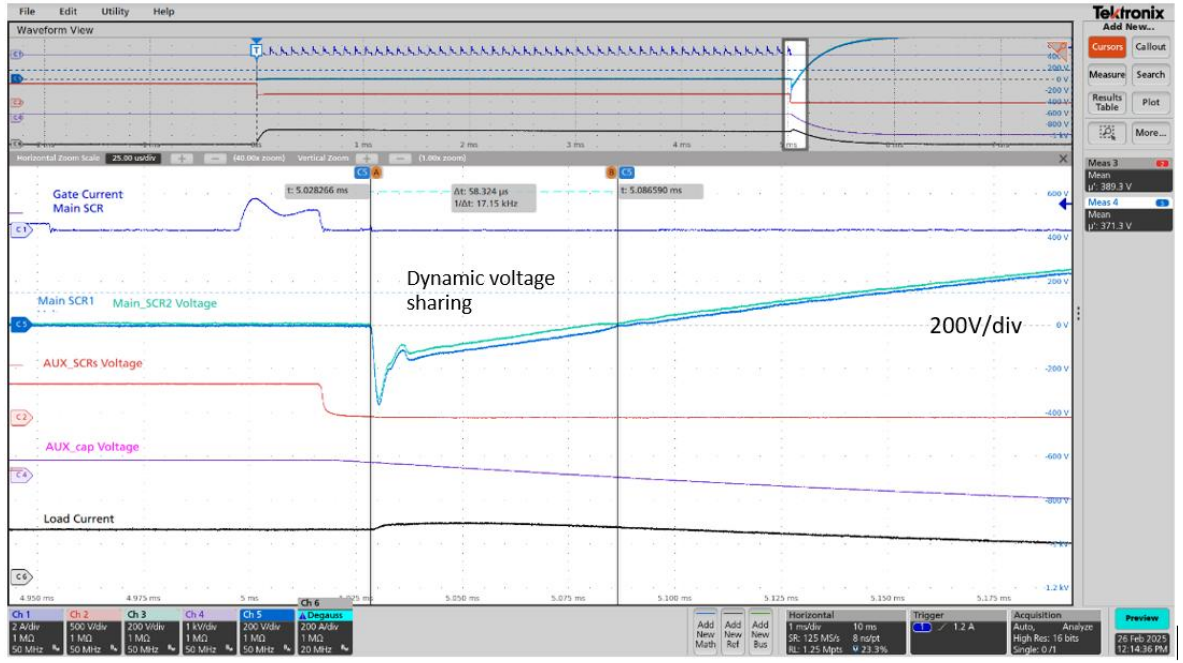
- Team has previously developed 3 kV class modular SCR based breaker.
- Team will use the knowledge to design, build and test a 5 kV 100 A solid state switch based on SCRs.
- Two 4 kV SCRs in series to implement the 5 kV class solid state switch



3 kV Class SSCB prototype



Gate driver capable of driving two SCRs simultaneously



Ref: M. L. Magri Kimpara, R. P. Kandula and E. T. Andrade, "3 kV-Class Scalable SCR-Based Solid State Circuit Breaker," 2025 IEEE Energy Conversion Conference Congress and Exposition (ECCE), Philadelphia, PA, USA, 2025, pp. 1-8, doi: 10.1109/ECCE58356.2025.11260045.

Conclusion

- First prototype of FMS was assembled and tested.
- Preliminary results demonstrate that the prototype is operating as intended.
- The results obtained thus far provided valuable data for evaluating the prototype's performance, identifying its limitations, and guiding future design refinements.
- Successfully opened the main contacts with less than 1ms.

Impact

- Enables protection for DC distribution systems
- Submitted a journal paper to IEEE Access related to the designed Thomson coil actuator.
- Submitted an invention disclosure mainly focused on the damping mechanism.

Future Direction/Next steps

- The mechanical design will be revised, and testing will continue at higher voltages. The issues to be addressed will be focused on:

  - Mechanical structure reinforcement
  - Overall mass reduction of the moving parts

- Integration with the solid-state switch to realize the hybrid switch and test at rated conditions.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE).

References

[1] M. L. Magri Kimpara, R. P. Kandula and E. T. Andrade, "3 kV-Class Scalable SCR-Based Solid State Circuit Breaker," 2025 IEEE Energy Conversion Conference Congress and Exposition (ECCE), Philadelphia, PA, USA, 2025, pp. 1-8, doi: 10.1109/ECCE58356.2025.11260045.

[2] B. Lequesne, T. Holp, S. C. Schmalz, R. M. Slepian and H. Wang, "Frequency-Domain Analysis and Design of Thomson-Coil Actuators," in IEEE Transactions on Industry Applications, vol. 59, no. 2, pp. 1765-1774, March-April 2023, doi: 10.1109/TIA.2023.3235345.

[3] D. S. Vilchis-Rodriguez, R. Shuttleworth and M. Barnes, "Modelling Thomson Coils With Axis-Symmetric Problems: Practical Accuracy Considerations," in IEEE Transactions on Energy Conversion, vol. 32, no. 2, pp. 629-639, June 2017, doi: 10.1109/TEC.2017.2651979

U.S. DEPARTMENT of ENERGY

Thank You!

OAK RIDGE National Laboratory

Tasks and Timeline

	Task Number	Task	Start Date	Completion Date
	1.0	Project Management	10/01/25	9/30/27
Thomson coil development	2.0	Fast Mechanical Switch (FMS) Development	10/01/25	9/30/26
	2.1	Design a 5 kV 100 A FMS	10/01/25	12/30/26
	2.2	Build a 5 kV 100 A FMS	3/30/26	6/30/26
	2.3	Develop the impulse driver circuit	04/01/2026	07/30/26
	2.4 (G/NG)	Test the first FMS prototype to provide necessary physical separation for 2-5 kV within 1 mS.	08/01/26	9/30/26
	2.5	Redesign and build the FMS prototype based on the experimental results of first prototype	10/01/26	12/30/26
	2.6	Test the second FMS prototype to provide necessary physical separation for 5 kV within 1 mS.	1/1/27	03/30/27
Solid state switch	3.0	SCR based Solid State Switch Development	10/01/26	7/30/27
	3.1	Design, build and test gate drives for 4 kV SCRs	10/01/26	12/30/26
	3.2	Design and build a 5 kV 100 A solid state switch using two 4 kV SCRs.	1/1/27	03/30/27
	3.3(G/NG)	Test the 5 kV solid state switch at 100 A for breaker operation	04/01/27	7/30/27
Integrated testing	4.0	Integrate FMS and SSS and test at 5 kV and 100 A and demonstrate < 1 mS opening time.	08/01/27	9/30/27