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# **ALE3D Magneto-Hydrodynamic (MHD) Modeling of a New ARL Squeeze 5 Magnetic Flux Compression Generator**

**by George B Vunni, Anthony Johnson, and Peter Bartkowski**

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# **ALE3D Magneto-Hydrodynamic (MHD) Modeling of a New ARL Squeeze 5 Magnetic Flux Compression Generator**

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## Contents

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<b>List of Figures</b>	<b>iv</b>
<b>Acknowledgments</b>	<b>v</b>
<b>1. Introduction</b>	<b>1</b>
<b>2. Description of the New ARL MFC Device</b>	<b>1</b>
<b>3. Experimental Measurement of the Inductance</b>	<b>2</b>
<b>4. Simulation</b>	<b>4</b>
4.1 Brief Description of the ALE3D-MHD Model	4
4.2 ALE3D Preshot Inductance Simulation: Model Description	5
4.3 Inductance Calculations: Model Results	6
<b>5. Simulation Result</b>	<b>7</b>
5.1 Inductance Result Interpretation	7
5.2 Comparison of the Inductance Simulation with Experiment	9
<b>6. Full ALE3D-MHD Simulation</b>	<b>10</b>
<b>7. Conclusion</b>	<b>12</b>
<b>8. Future Experimental Suggestions</b>	<b>12</b>
<b>9. References</b>	<b>13</b>
<b>List of Symbols, Abbreviations, and Acronyms</b>	<b>14</b>
<b>Distribution List</b>	<b>15</b>

## List of Figures

---

Fig. 1	Schematic drawing of the new Squeeze 5 generator design .....	2
Fig. 2	An illustration of inductance measurement in a mock generator showing the positions of the aluminum cone.....	3
Fig. 3	Plot of measured inductance vs. axial position of cone .....	4
Fig. 4	Geometric model used in in ALE3D for the inductance calculation showing the MFC device, mesh, and external circuit.....	5
Fig. 5	ALE3D simulation configuration showing the aluminum cone offset position.....	6
Fig. 6	Plot of the current output for different offset positions .....	6
Fig. 7	Inductance calculations: results interpretation.....	7
Fig. 8	Comparison ALE3D and analytic fit of current flow through the model for the a) 2.54-cm and b) 25.4-cm aluminum cone offset .....	8
Fig. 9	Comparison of the ALE3D simulations and measured inductance vs. aluminum cone position.....	9
Fig. 10	Percentage difference of ALE3D simulation .....	10
Fig. 11	Comparison of ALE3D-MHD simulation (red line) and experimental current trace (blue line) for a) 110-kA seed current and b) $\dot{I}$ .....	11

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## 1. Introduction

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Magnetic flux compression (MFC) generators are attractive energy sources for a compact pulsed-power system. The helical MFC consists of a conducting cylindrical coil (stator) and a conducting cylindrical tube (armature) filled with high explosives.<sup>1</sup> The stator is energized by a seed current with a return path via the load and armature. When initiated, the explosive in the armature rapidly expands the armature along its axial length. In order to protect the seed current source from the MFC, its output is shorted by a crowbar switch that engages just as the stator begins to expand. As the detonation moves forward, the stator coil is shorted out turn by turn by the armature, resulting in the reduction of the circuit inductance and increase of the current in the device due to conservation of magnetic flux.

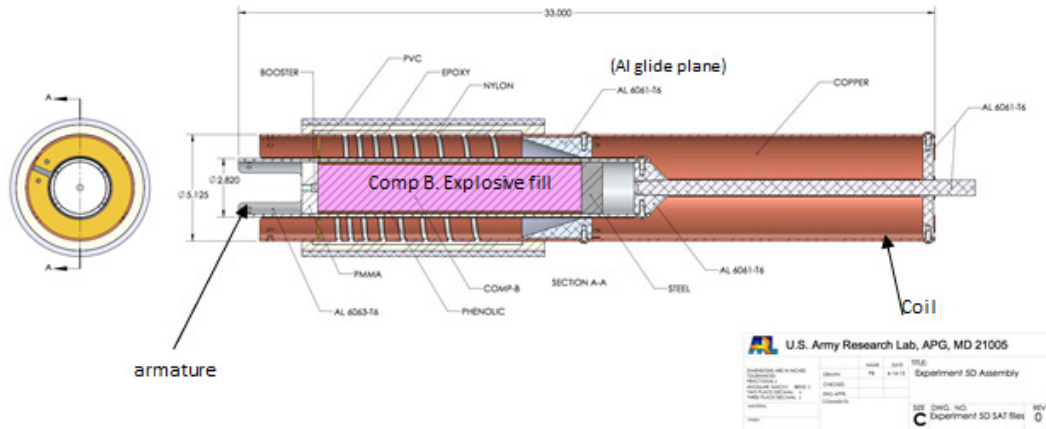
To optimize the design of a complete MFC system, the system needs to be accurately modeled. Magneto-hydrodynamic (MHD) simulations can be a very powerful tool to help design and analyze MFC devices. In this report, we cover ALE3D-MHD prediction of inductance and output current of a new MFC device developed and tested by US Army Research Laboratory (ARL).<sup>2</sup> Our purpose in the present work is to establish a set of simulation techniques and parameters in ALE3D that produce similar results to the experimental data. This will allow us to use the ALE3D-MHD code to model the performance of this MFC generator and optimize future device designs before fabrication and testing. The outputs of interest for this work focus on the MFC internal inductance with time and current output.

## 2. Description of the New ARL MFC Device

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The ARL Squeeze 5 helical flux compression generator is derived from the Squeeze 4 design.<sup>3,4</sup> The device has a C12200 copper coil with a 6063-TO aluminum armature. A schematic drawing of the Squeeze 5 device is shown in Fig. 1. The armature tube has a 71.6-mm outer diameter and 4-mm wall thickness. A phenolic resin tube with 3-mm wall thickness is filled with Composition B explosive and inserted into the armature just prior to the flux compression experiment. The variable pitch coil is machined from a 130-mm outer diameter copper tube. A 6.4-mm slot is cut into the tube, using a 4-axis mill, to create a 7-turn coil. The coil conductor width is smallest at the initiation end of the device and grows in width to its maximum at the generator's end. This provides the generator with an additional conductor cross section as the current builds in the device during its function.



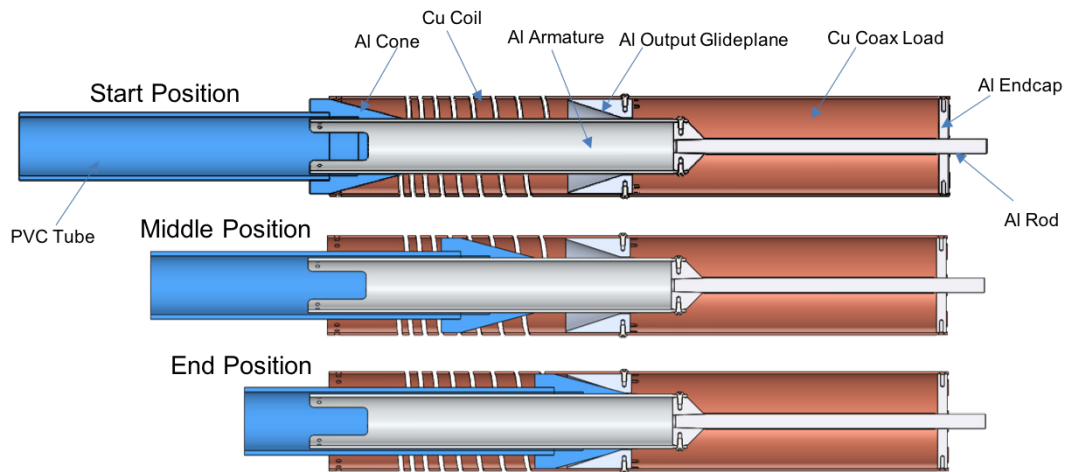
**Fig. 1 Schematic drawing of the new Squeeze 5 generator design**

The slot (coil gap) is filled with a 3-D printed plastic form that insulates adjacent coil windings and the exterior of the coil. The outer surface of the stator is insulated by a layer of epoxy that is poured into the gap between the stator and as coaxial PVC tube that has an outer diameter of 168 mm and a 7.1-mm wall thickness. A slotted 1.5-mm-thick brass disc with an inner diameter slightly larger than the diameter of the armature is used as a crowbar at the initiating end of the device to electrically isolate the capacitor bank from the compressor output. The slot prevents the formation of eddy currents in the disc prior to crowbar actuation. The far end of the generator has an output glide plane machined from 6061-T6 aluminum. The glide plane has an angle of  $18^\circ$  and forms the transition to the benchtop load. The benchtop load is a simple coaxial inductor formed by the outer copper tube with the same diameter as the coil and an inner 19-mm 6061-T6 aluminum cylinder connected to the armature through a tapered transition section. An endcap machined from 6061-T6 aluminum connects the tube to the inner cylinder. High-pressure contacts are used at the tube-to-endcap connection to minimize resistance. A Rogowski coil inside the load measures output current from the generator.

### **3. Experimental Measurement of the Inductance**

The temporal variation of the generator inductance ( $L$ ) was inferred by taking inductance measurements of the system with a metallic conical conductor (shorted across the armature and the mock generator coil) at various axial locations. The angle of the metallic (aluminum) cone was set to slightly less than the predicted Gurney angle (expansion angle), and the inductance at each position was measured using an Agilent Technologies E4980A Precision LCR meter. Moving the conical insert along the axis of the stator is meant to mimic the expansion of the armature during MFC operation.

The inductance measurements were taken every 1.27 cm (0.5 inch) along the axis at a frequency of 5 kHz, which matches the frequency of the actual flux compression seed current. As the conical metal insert moves from the start to the end position at burnout, it shorts out turns and reduces the generator inductance. Inductance versus time can be determined by dividing the cone position by the detonation wave velocity of the explosive fill in the armature. Figure 2 is an illustration of the inductance measurement through a mock generator using the aluminum cone expansion technique. The plot of the measured inductance versus the axial position is shown in Fig. 3. At the initial inductance (zero cone position), the inductance was approximately  $2.4 \mu\text{H}$  (2400 nH), and approximately  $0.22 \mu\text{H}$  (220 nH) at the final cone position of 30 cm.



**Fig. 2** An illustration of inductance measurement in a mock generator showing the positions of the aluminum cone

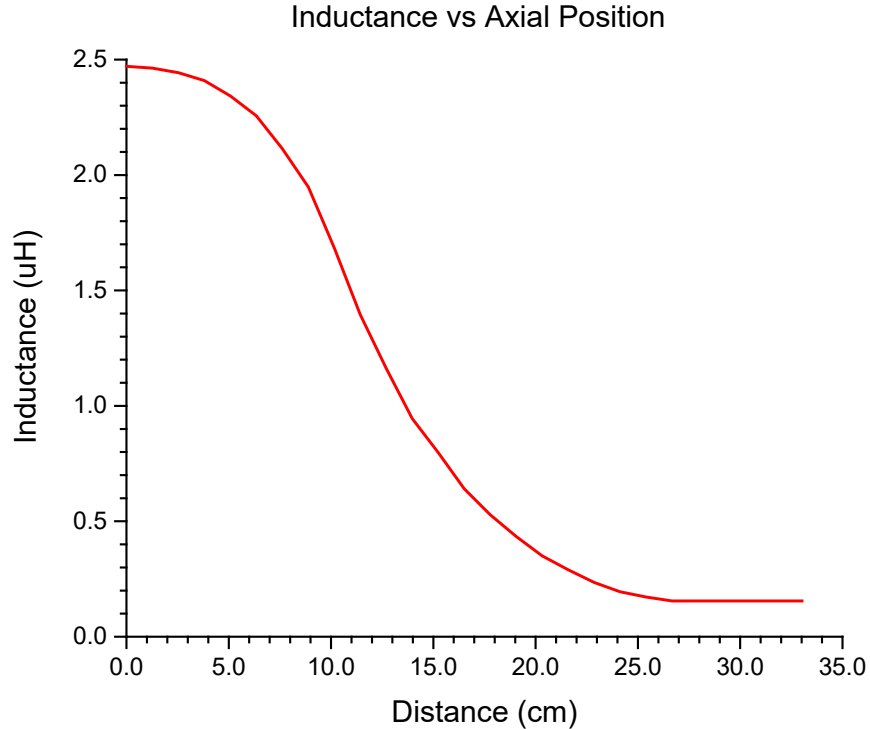


Fig. 3 Plot of measured inductance vs. axial position of cone

## 4. Simulation

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### 4.1 Brief Description of the ALE3D-MHD Model

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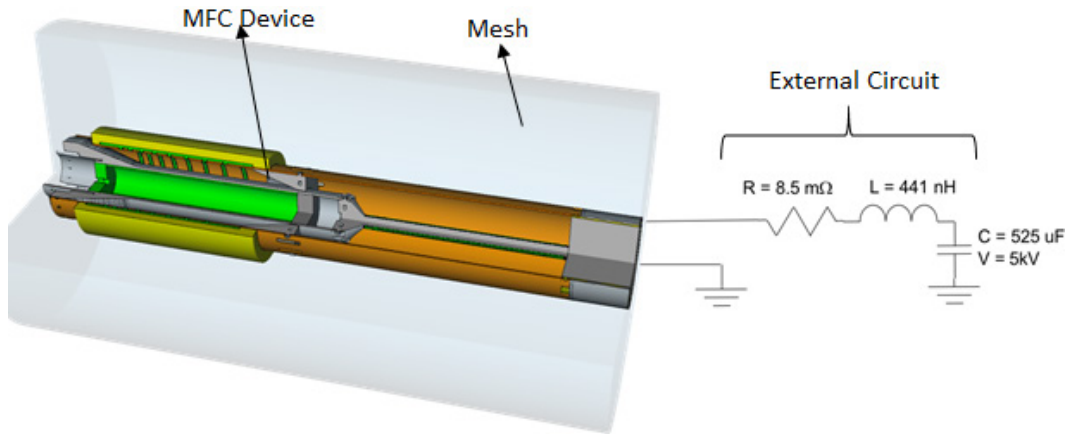
Simulations were performed using ALE3D-MHD, a 3-D multiphysics numerical simulation software tool using arbitrary Lagrangian-Eulerian techniques developed by Lawrence Livermore National Laboratory (LLNL).<sup>2</sup> The ALE3D-MHD model is capable of capturing the dynamics of electrically conducting solids and fluids. The MHD module was developed for the modeling of coupled electro-thermal-mechanical systems that are inherently 3-D in nature.

The ALE3D-MHD module solves the resistive magnetic induction equation given a collection of specified current and voltage sources. The equation is solved in the Lagrangian frame using a mixed finite-element method employing  $\nabla \times \mathbf{H}$  and  $\nabla \cdot \mathbf{H}$  finite-element basis functions, which preserves the solenoidal nature of the magnetic field. Electromagnetic force and resistive joule heating terms are coupled to the equations of motion and thermal diffusion in an operator split manner.<sup>2</sup> For problems that require mesh relaxation (explosively driven MFC devices), magnetic advection is performed using the method of algebraic constrained transport that is valid for unstructured hexahedral grids with arbitrary mesh velocities. The advection method maintains the divergence-free nature of the magnetic field and is

second-order accurate in regions where the solution is sufficiently smooth. For regions in which the magnetic field is discontinuous (e.g., MHD shocks), the advection step is limited using the method of algebraic flux correction, which is local extremum diminishing and divergence preserving. Details pertaining to the ALE3D-MHD model can be found in Anderson et al.<sup>2</sup>

## 4.2 ALE3D Preshot Inductance Simulation: Model Description

Figure 4 shows the geometric model used in ALE3D for the inductance calculation. The geometry was taken from a Solidworks software 3-D solid model. The solid model was then shaped into the full 3-D mesh (model geometry shown as illustrated in Fig. 4). A coaxial feed section was added to the output end of the generator to feed current into and out of the simulation. For these inductance simulations, a lower initial charge voltage (5 kV) was used than in the experimental flux compression experiment (10 kV) to reduce the current and thereby ohmic heating to keep the temperature of the materials low. The resistor (8.5 m $\Omega$ ) and inductance (441 nH) were chosen to replicate the 5-kHz frequency used in the experimental measurement. In the inductance measurements, the LCR meter uses a very low current that does not cause any measurable ohmic heating of the materials.



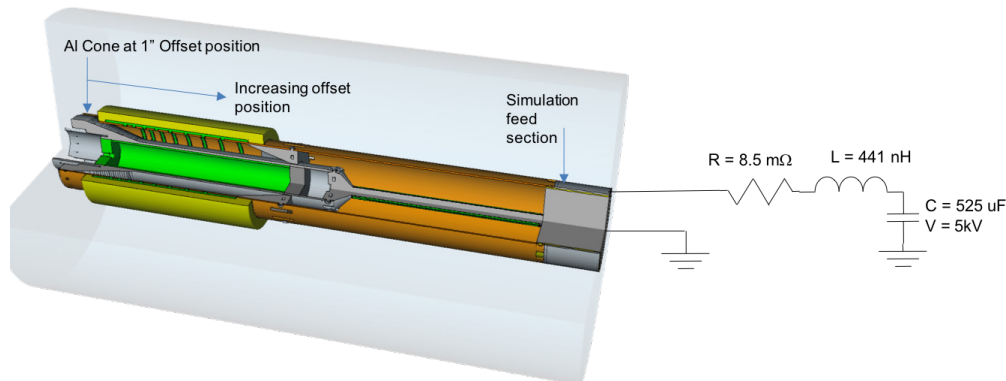
**Fig. 4** Geometric model used in in ALE3D for the inductance calculation showing the MFC device, mesh, and external circuit

The coaxial feed section has a thin gap (2 mm) at a high radius (~60 mm) to make inductance of this section small (L of this section is less than 1 nH). In the simulation, the position of the metallic cone was varied to replicate the range of positions used in the inductance measurements described in section 3 of this report. The model mesh (simulation domain) was connected to an external circuit that simulated a capacitor bank and transmission line. A transient MHD analysis was run at each of the various axial aluminum cone positions. This simulation was effectively the same as a “ringdown” (short-circuiting) experiment. The capacitor

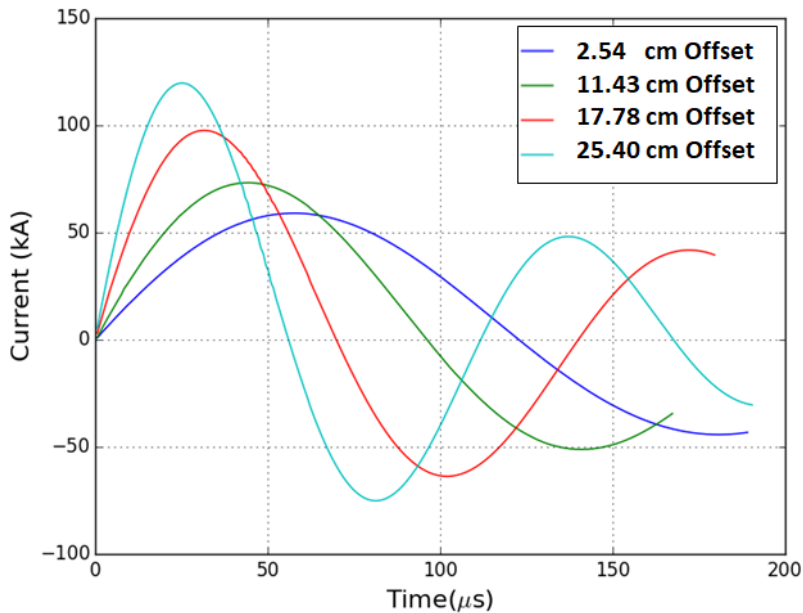
bank and transmission line parameters are similar to those used in the full-pulsed experiment (e.g., similar to seed bank), so initial frequency is the same as the actual flux compression experiment seed current.

### 4.3 Inductance Calculations: Model Results

A number of cone positions were modeled. Figure 5 illustrates the aluminum cone position at the 2.54-cm offset position; arrows indicate the increasing offset position and the simulation feed section. Current pulses from subset for a series of aluminum cone offset positions are shown in Fig. 6.



**Fig. 5** ALE3D simulation configuration showing the aluminum cone offset position

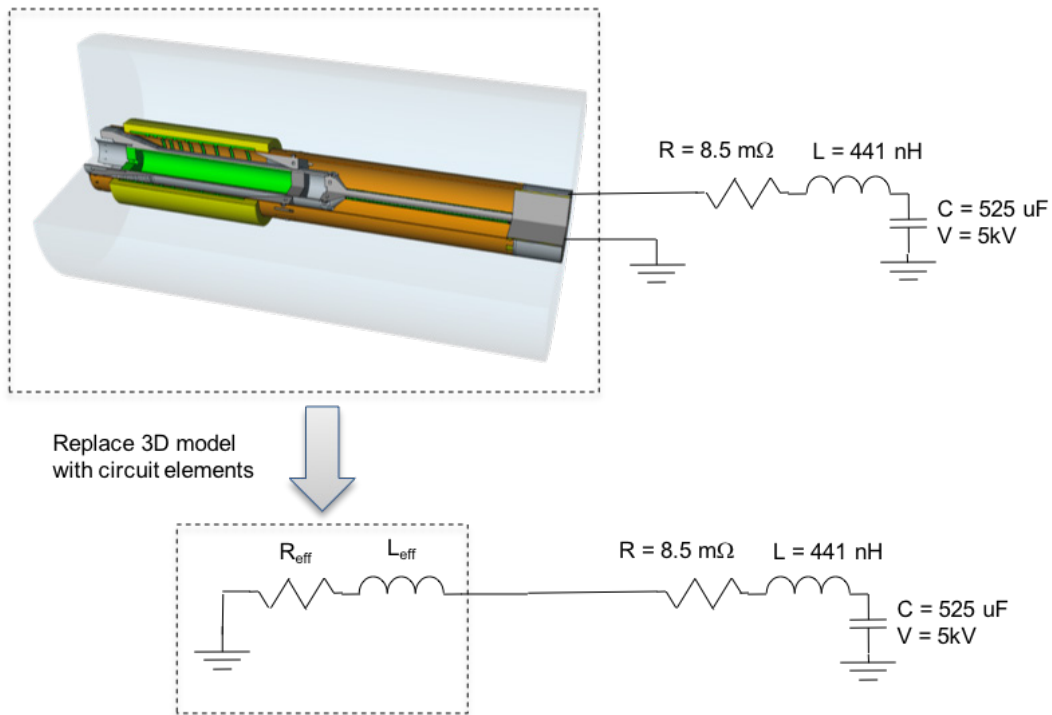


**Fig. 6** Plot of the current output for different offset positions

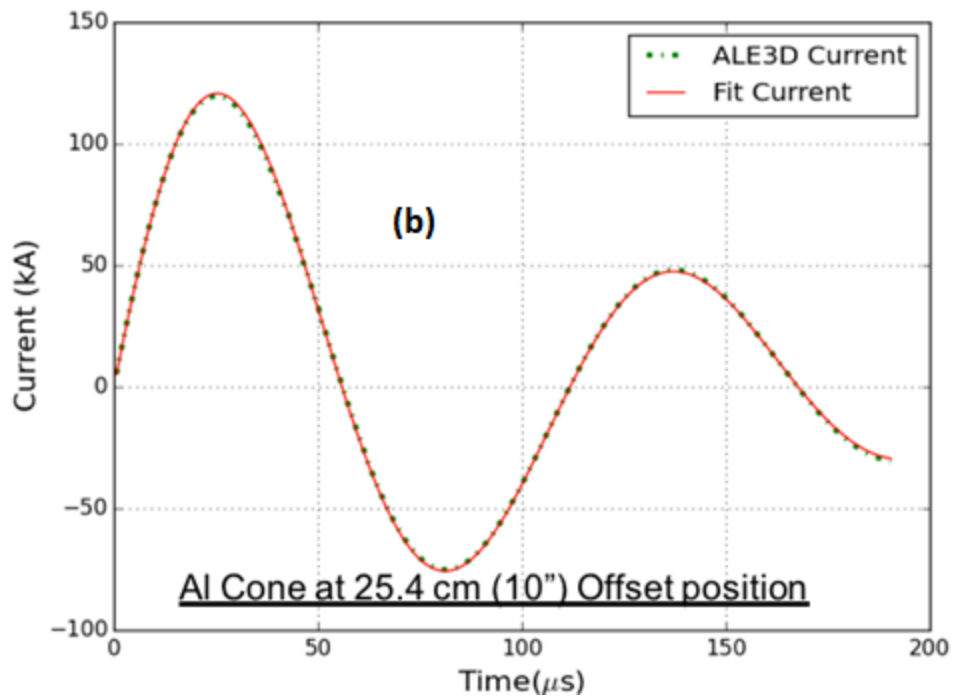
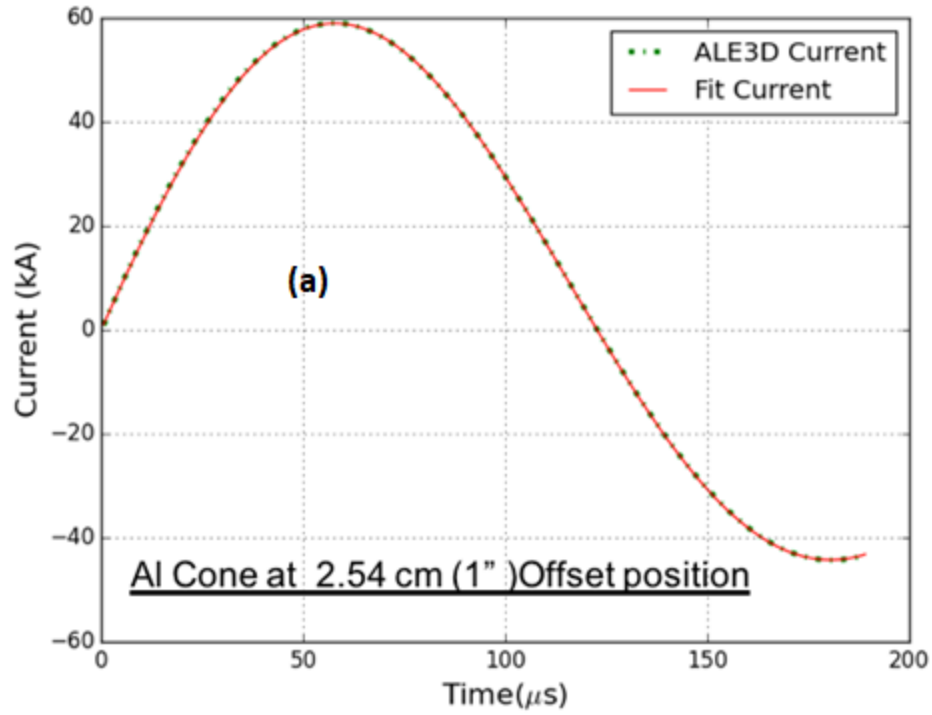
## 5. Simulation Result

### 5.1 Inductance Result Interpretation

An analytical inductance was determined by treating computational volume as a lumped circuit element with an effective inductance ( $L_{\text{eff}}$ ) and resistance ( $R_{\text{eff}}$ ). The 3-D computational model was replaced with lumped circuit elements. A fitting algorithm (differential evolution) was then applied to this to calculate  $L_{\text{eff}}$  and  $R_{\text{eff}}$  of the computational volume based on the simulation results. Figure 7 shows a schematic of the circuit model analysis. The analytical fit for the  $L_{\text{eff}}$  shown in Fig. 7 was compared to the ALE3D current simulation results for the 2.54-cm (1-inch) and 25.4-cm (10-inch) offset. Figure 8 shows the comparison of the analytical fit and the simulation result, which agrees very well.



**Fig. 7 Inductance calculations: results interpretation**



**Fig. 8 Comparison ALE3D and analytic fit of current flow through the model for the a) 2.54-cm and b) 25.4-cm aluminum cone offset**

## 5.2 Comparison of the Inductance Simulation with Experiment

The plot of the effective inductance ( $L_{\text{eff}}$ ) from the ALE3D simulation fits and the measured inductance change versus cone position is shown in Fig. 9. The inductances calculated from the ALE3D simulations show a very good agreement with the measured values (at both ends of the device). However, differences of as much as 10% to 15% are seen in the 20.32-cm (8-inch) and 25.4-cm (10-inch) offset cases. Figure 10 shows a plot of the simulated and experimental percent difference. The difference observed may be due to frequency dependence in the measurement and simulation. The experimental measurements were taken at a fixed frequency of 5 kHz, but the frequency varied in simulation as the inductance was reduced. Another possible difference could be due to mesh resolution (this is always a possibility). Because the experimental data do not have error bars in either axis, a small axial shift (2–5 mm) may cause a large fraction of the observed difference.

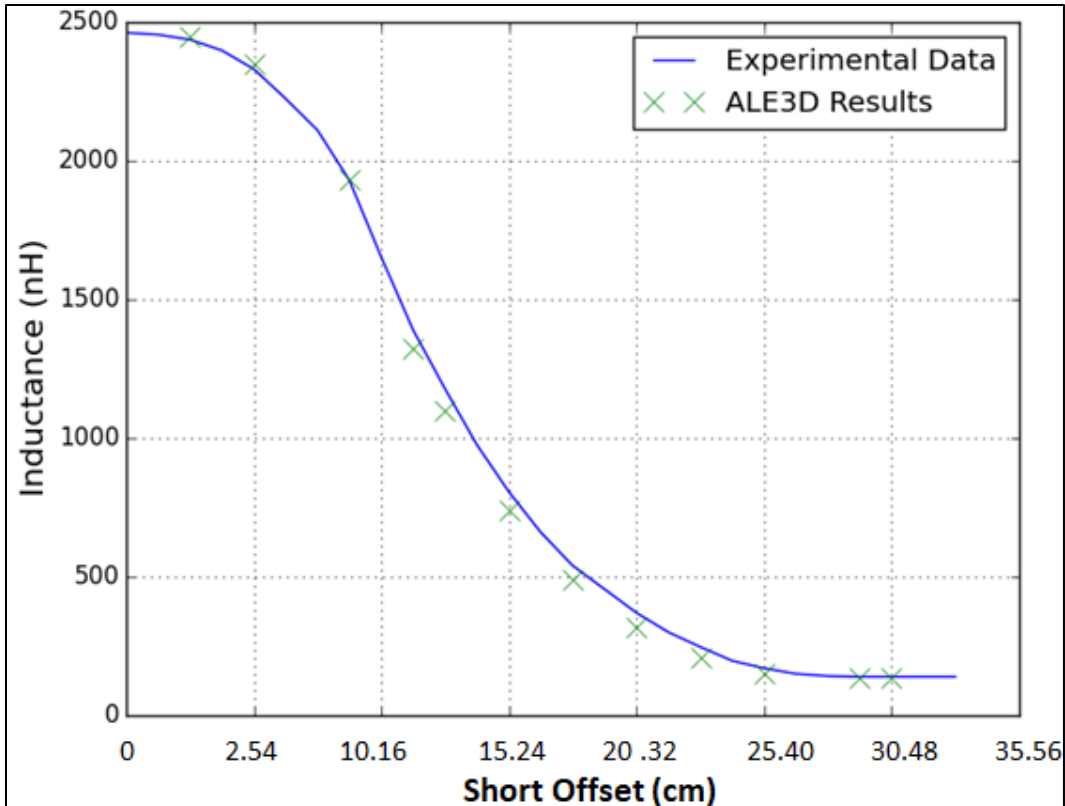


Fig. 9 Comparison of the ALE3D simulations and measured inductance vs. aluminum cone position

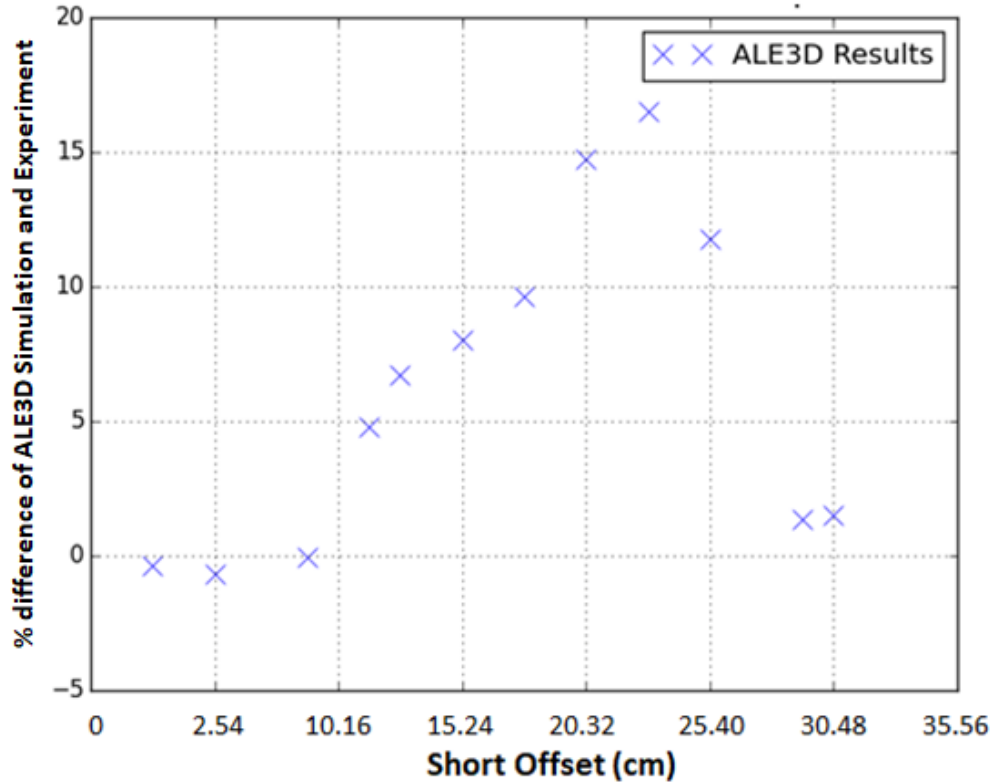
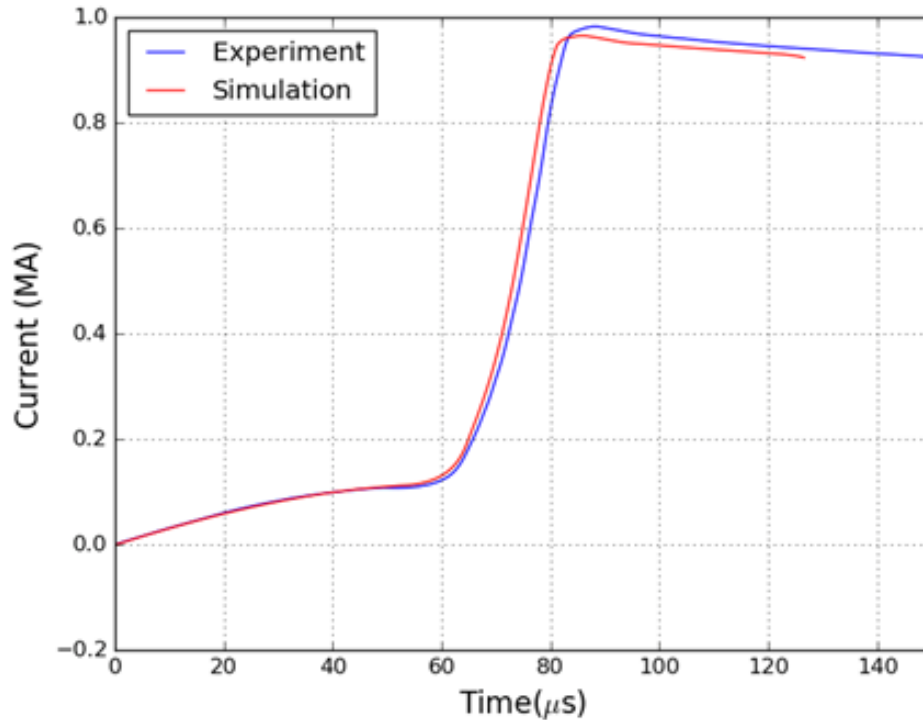


Fig. 10 Percentage difference of ALE3D simulation

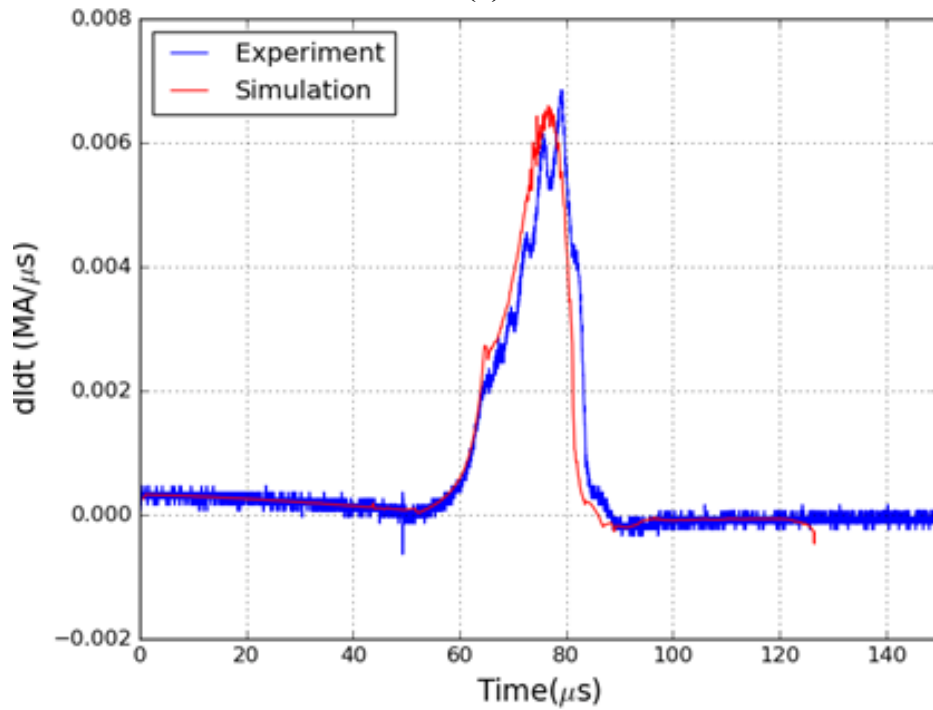
## 6. Full ALE3D-MHD Simulation

After the inductance simulations, a full MHD simulation was conducted to investigate the performance of the flux compression generator in operation. In the simulation, the current was injected with external seed capacitor bank and transmission line. The parameters of the experimental feed circuit were determined to be  $L = 221 \text{ nH}$ ,  $C = 525 \text{ }\mu\text{F}$ , and  $R = 7.5 \text{ m}\Omega$  from the experimental data. To get the seed pulse to align closer to the value measured in the experiment, the feed inductance was adjusted to  $691 \text{ nH}$  in the simulation. The Composition B high explosive was modeled using Jones-Wilkens-Lee model (line-of-sight lighting time). The detonation time was tuned to crowbar at approximately the same time as in the experiment. This was done by comparing simulated current and I-dot signals with the experimental data.

Figure 11 shows the current and I-dot profiles from ALE3D-MHD simulations and experiments for one experiment with 110-kA seed current. The agreement between simulation and experiment is reasonable for the first  $60 \text{ }\mu\text{s}$  before the peaking of the current. The simulation under predicted the maximum current. The simulated maximum current was 956 kA, approximately 3% less than the measured peak current of 982 kA.



(a)



(b)

**Fig. 11 Comparison of ALE3D-MHD simulation (red line) and experimental current trace (blue line) for a) 110-kA seed current and b)  $I.\dot{}$**

## 7. Conclusion

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In this work, the results of a 3-D numerical study of the ARL-designed MFC generator using ALE3D-MHD code from LLNL are presented. Results of ALE3D inductance simulations of the Squeeze 5 MFC device was compared with the experimental data. The following results were observed:

- 1) Inductance Calculations. The agreement was very good at both ends of the generator, but not as good in the middle of the generator. We recommend running these calculations in a “fixed frequency” mode. For example, apply a prescribed current waveform, extract voltage, and repeat the fitting procedure to voltage instead of current. Also, we recommend quantifying the experimental uncertainties, both in inductance and position space.
- 2) Transient Flux Compression Calculations. Analysis results are quite close to the experiment. We expected the simulation to overshoot the experimental current, but the opposite occurred. Also studying advection/mesh resolution controls may reveal if there is anything prematurely stopping compression of the flux. Running a case with L/C/R equal to values provided by the experimental data reported in Bartkowski<sup>3</sup> and Vunni<sup>4</sup> may reveal if there is anything prematurely stopping compression of the flux. However, this may require different detonation timing, allowing the plastic insulator to break down, and lower charge voltage (i.e., how accurately do we know capacitor voltage?).

## 8. Future Experimental Suggestions

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To improve our modeling methods and validate some of the experimental data, we suggest a direct measure of the hydrodynamics. This would help with bounding the inputs of the model (errors bars associated with the ALE3D models). Other experimental diagnostics to be done include measuring the metal-to-metal contact at the crowbar and determining the motion of the armature with photon Doppler velocimetry. We also suggest that a separate measure of the seed bank current and voltage be done in each experiment. This additional experimental data will help bound the inputs of the simulation and allow modelers to focus on the details that matter.

## 9. References

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## List of Symbols, Abbreviations, and Acronyms

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3-D	three-dimensional
ARL	US Army Research Laboratory
L	inductance
$L_{\text{eff}}$	effective inductance
LLNL	Lawrence Livermore National Laboratory
MFC	magnetic flux compression
MHD	magneto-hydrodynamic
$R_{\text{eff}}$	effective resistance

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