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High Current Output of ARL's Bifurcated Stator Flux Compression Generator

by George B Vunni and Anthony J Johnson

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14. ABSTRACT

The US Army Combat Capabilities Development Command Army Research Laboratory developed two helical flux compression generators (FCGs) called Squeeze 5C and Squeeze 5D. This devices were expected to deliver up to 2.0 MA of current to an inductive load of 160 nH. This report presents simulation results of ARL’s bifurcated stator FCG. The design allows for a current output delivering up to 1.0 MA, approximately 8% gain from the original design. We describe the modified design of the two generators and the use of ALE3D-magneto-hydrodynamic (MHD) simulation.

15. SUBJECT TERMS

Squeeze 5, magnetic flux compression, coil winding, stator, ALE3D, MHD, flux compression generator

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1. Introduction and Background

Over the past 5 years, the US Army Combat Capabilities Development Command Army Research Laboratory has been developing a family of flux compression generators (FCGs) called "Squeeze" to provide energy for pulsed-power experiments. The objective of the FCG research project at DEVCOM Army Research Laboratory is to design an FCG device that could generate output currents of approximately 2.0 MA.[1–3] Bartkowski and Berning[4] built and tested the performance of a helical flux compression generator. Over the past 3 years, variations were made in the design of the FCG device to improve the current output. However, the designs failed to produce the required output current of 2.0 MA.

The efficiency of an FCG device is highly dependent on the expanding characteristics of the exploding armature and the nature of the contact between the armature and the surrounding stator (coil). The energy-conversion process comprises two steps: primary energy of the high explosives to kinetic energy of the expanding armature, and the kinetic energy of the armature to the final electromagnetic energy.

The current family of the "Squeeze" FCG design has been inefficient at converting the explosive energy due to loss of magnetic flux. In an attempt to address the inefficiency, design, modifications were made in the stator (coil). The purpose of this study is to use numerical modeling to improve the design and performance of the FCG at lower seed current (110 kA) using the ALE3D-magneto-hydrodynamic (MHD) code.

This report is organized as follows. First, the ARL FCG family of designs is reviewed. Second, the modification of the design is described. Third, the ALE3D-MHD code and its capabilities are outlined, and simulation setup for the design is described. Finally, ALE3D-MHD[5] simulations are examined and comparisons are made to the experimental results.

2. Brief Description of the "Squeeze" FCG Devices

ARL has two FCG designs, "Squeeze 5C" and "Squeeze 5D". Details of the Squeeze 5C FCG device has been extensively described in Vunni et al.[1,2] In brief, the Squeeze 5C device has a C12200 copper stator (coil) with a 6063-TO aluminum armature. Figure 1 shows a schematic drawing of the device. The armature tube has a 71.6-mm outer diameter and 4-mm wall thickness. A phenolic resin tube with 3-mm wall thickness was filled with Composition B explosive and inserted into the armature the day of the flux compression experiment. The variable coil pitch was machined from a 130-mm outer diameter aluminum tube. A 6.4-mm slot was cut into the tube, using a 4-axis mill, to create a 7-turn coil. The coil's conductor width is smallest at the initiation end of the device and grows in width to its maximum at the output end of the generator. This increasing cross-sectional area of the conductor prevents coil melting or vaporization as the current builds in the device during its function. Figure 1 shows a cross section and a full 3-D image of the Squeeze 5 FCG device.

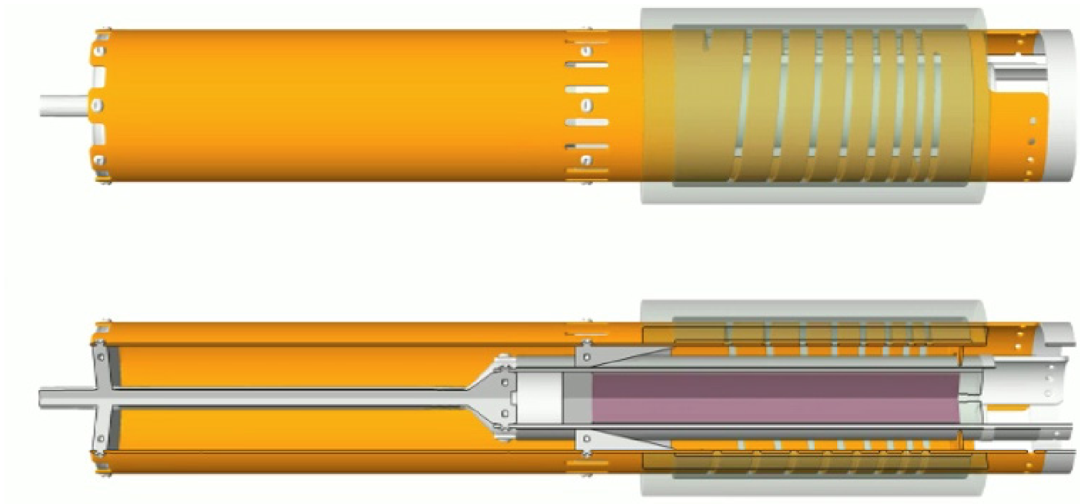

Fig. 1 Solid model of Squeeze 5C and cutaway view

3. Background of Squeeze FCG Modification

Figure 1 shows the solid geometry and cutaway of the Squeeze 5C FCG. In a previous work, ALE3D simulation was conducted to investigate the performance of the generator. Figure 2 shows the current prediction of the ALE3D simulation lines up reasonably well compared to the experimental data. The simulation underpredicts the final output current[1,2] by a few percent. While the simulation does not agree perfectly, it is still possible to use it to look for potential lost flux.

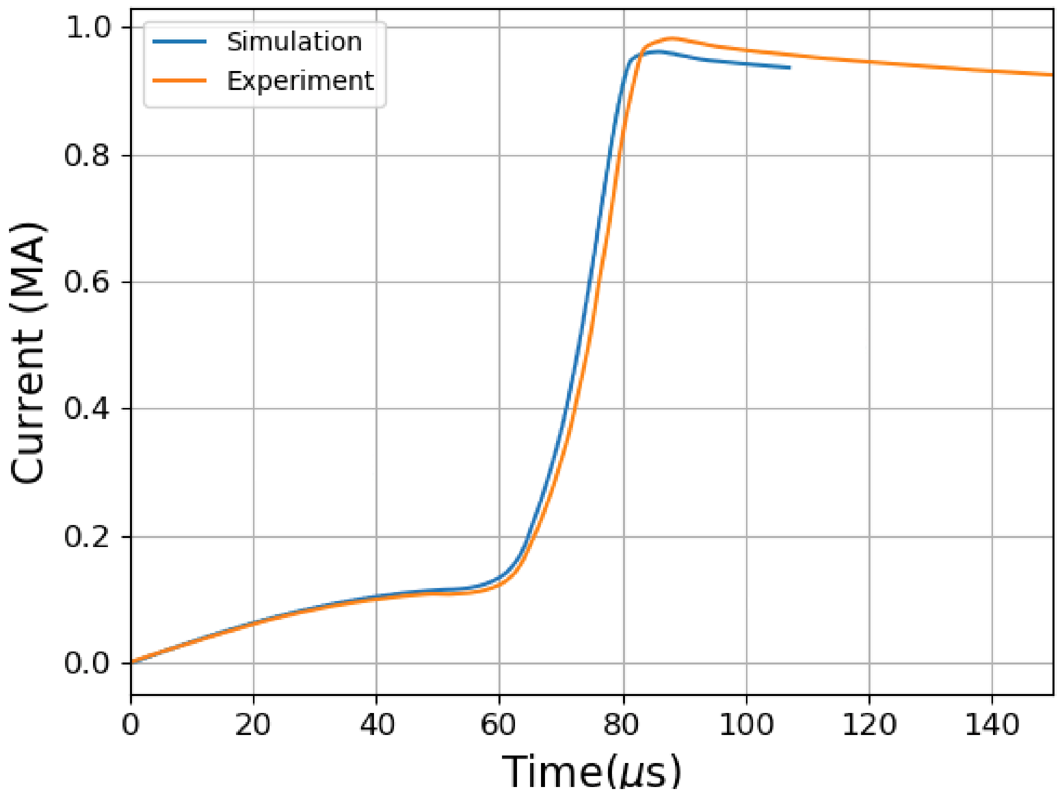

Fig. 2 Comparison of simulated and experiment current output of Squeeze 5 FCG

In the simulation of the Squeeze 5C generator,[1] we observed pockets of trapped flux that were excluded from compression between the first turn contact and at the end of the compression. Figure 3 shows an illustration of trapped regions of uncompressed magnetic flux.

In Fig. 3a, the armature expansion clearly shows the existence of an end effect,[6,7] causing a bell-shaped contour of the armature near the detonation side. This effect is caused by the open end where the detonation occurs. When the explosive is detonated, some of the detonation pressure escapes through the open end, which in turn reduces the outward expansion of the portion of the armature near this area. In any FCG design the end-effect is very important in minimizing magnetic flux losses resulting from the lack of contact between the armature and the stator (coil) within the region. The pocket region at the crowbar (illustrated in Fig. 3a) is a coaxial field section; however, a loss of small amount of magnetic flux in this region may influence the initial inductance of the generator. Previous simulation[1,2] has shown that the geometry of the crowbar is important in eliminating the trapped magnetic flux.

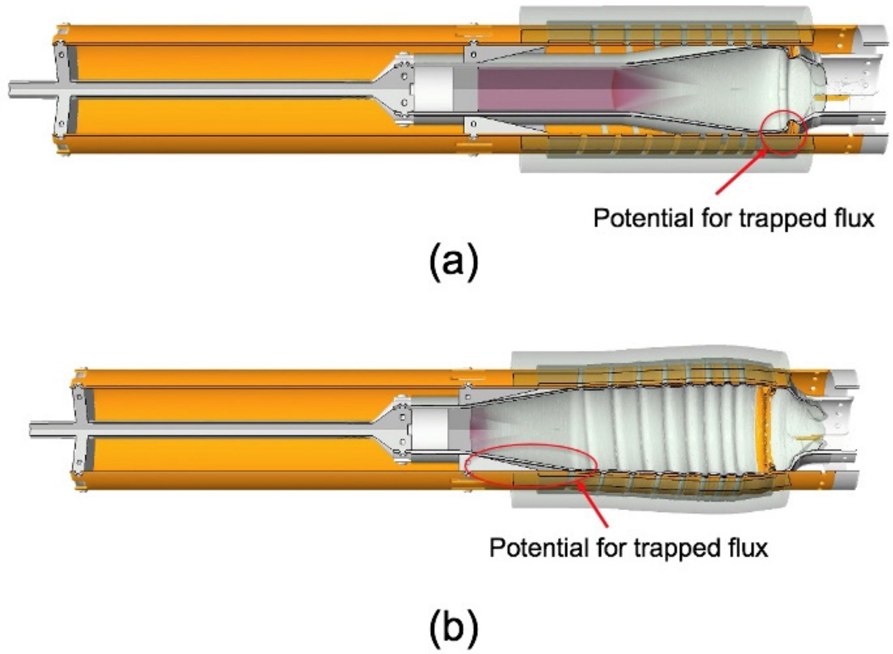

Fig. 3 Illustration of trapped magnetic flux at the a) crowbar section and b) the glide-plane section

Figure 3b shows another region where magnetic flux is trapped, at the glide plane. The trapped pockets of magnetic flux between the glide plane and the expanding armature are causing some losses in the final output of the generator, resulting in a lower compressed current. The trapped magnetic flux is sufficient to suppress the overall performance of the FCG device. In other words, the trapped region impedes the reduction in the FCG inductance, resulting in less current delivered to the load.

The Squeeze 5C FCG showed some design flaws in the crowbar and the glide plane. For efficient flux compression, the crowbar needs to switch fast such that little energy is dissipated during this process and contact is never lost during the armature's expansion. In order to address the design flaws in Squeeze 5C, two design changes were made. The crowbar in the original Squeeze 5C was changed from a copper disk with 2.54-cm thickness to a rounded edge with a cone section (glide plane) approximately 45°. To eliminate the motion of the crowbar, a plastic spacer was added behind the crowbar. The advantage of the modified crowbar is that the armature makes a complete contact with the stator (coil), thus eliminating the trapped magnetic flux region at the input end from the main generator.

In addition, the glide plane (cone section) was stretched to allow for better phasing of the armature near the generator output.[2,3] The reduction of the glide-plane angle serves to minimize pockets of trapped magnetic flux, resulting in a faster reduction of the overall FCG inductance and a higher current amplification. Figure 4 shows the modified geometry of the Squeeze 5C FCG called “Squeeze 5D”. Figure 5 shows the comparison of the modified FCG Squeeze 5D, and the original 5C.

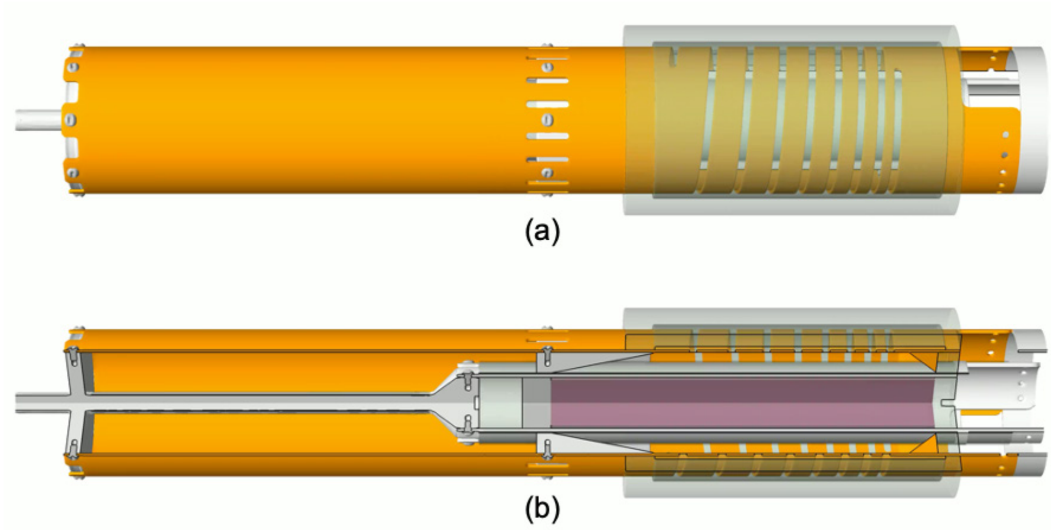

Fig. 4 Full geometry and cutaway model of the Squeeze 5D FCG

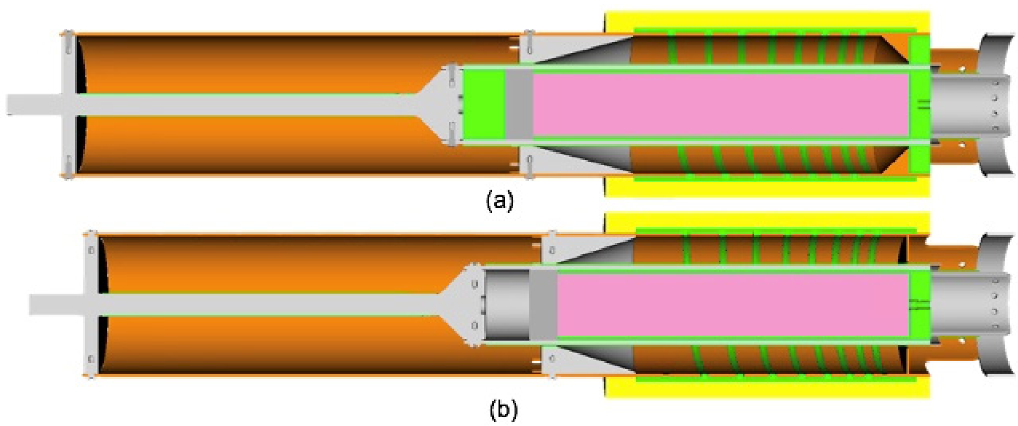

Fig. 5 A cutaway 3-D model of the image of the a) Squeeze 5D and b) Squeeze 5C FCGs

After the modification, we conducted ALE3D-MHD simulation to access the performance of the Squeeze 5D design using the same setup.[1,2] Figure 6 shows the current output compared to the measured current output of the Squeeze 5C. The current plot matches well up to approximately 82 μs and then slightly drops below the experimental current. The simulation predicted a maximum current of 973 kA, which differed from the experimental peak current of 980 kA by approximately 7 kA. The simulation is in good agreement with the experimental current output.

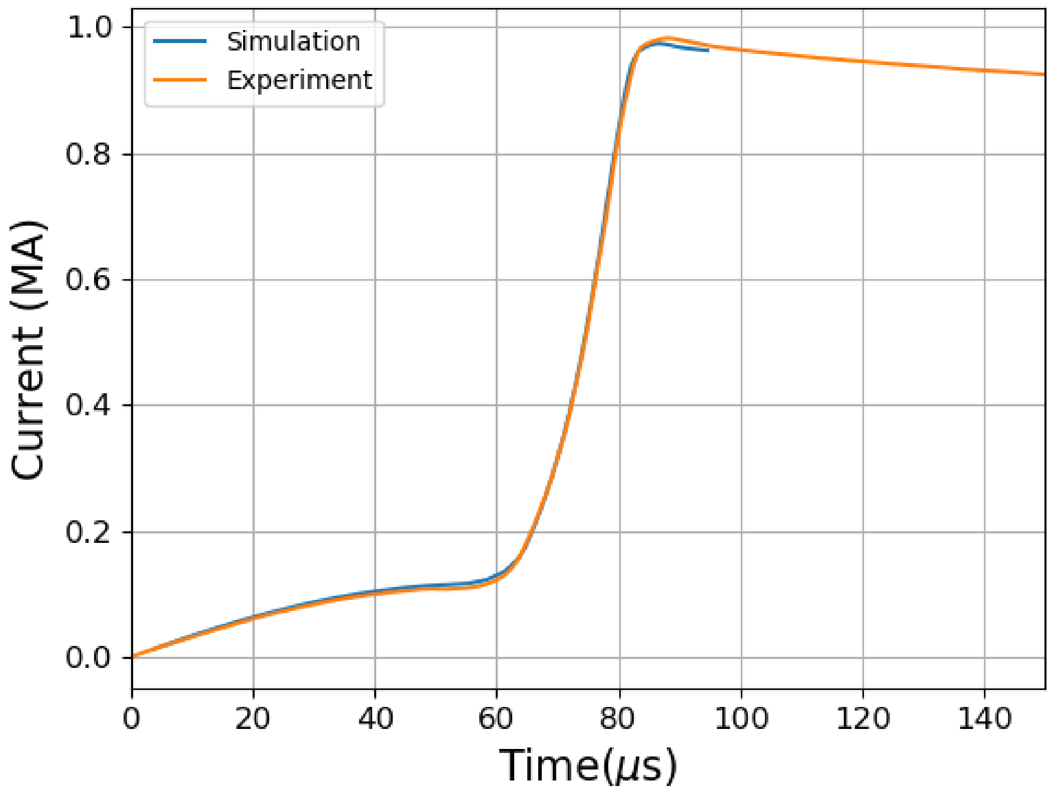

Fig. 6 Comparison of simulated current output of Squeeze 5D with the experimental data

During the simulation of Squeeze 5C and 5D FCG, we noticed a significant motion of the stator (coil) at the output end of helical slot. Figure 7 shows an illustration of this motion at the beginning, near the end of the shot, and just before the armature's impact at this location.

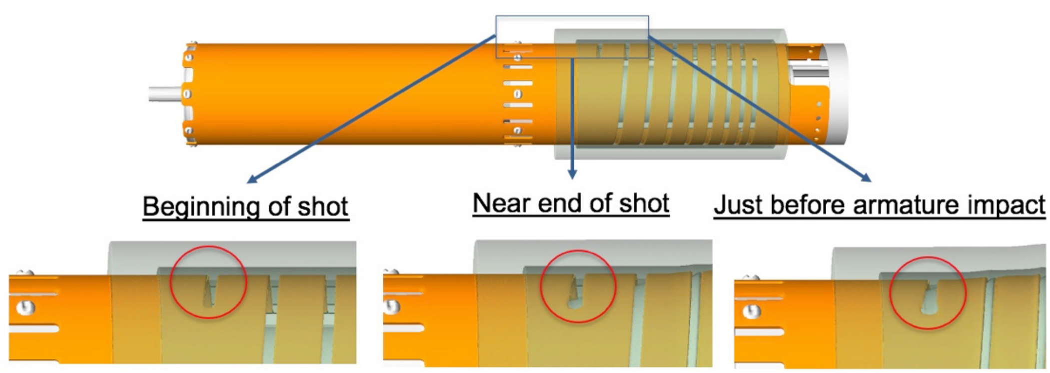

Fig. 7 Illustration of the stator (coil) motion at the end of the helical slot for Squeeze 5C. Similar observation was seen for Squeeze 5D FCG.

Figure 8 shows the comparison of 5C and 5D current pulses and time derivative (dI/dt). Changes from 5C to 5D resulted in slightly lower current (~2% lower) from the same seed source. This is a bit surprising; the reduced trapped flux volume should have resulted in a slightly larger current. The current plots show a delay in the 5D compression: it is crowbarring later in the pulse and the entire compression is lagged by approximately 1.5 μs.

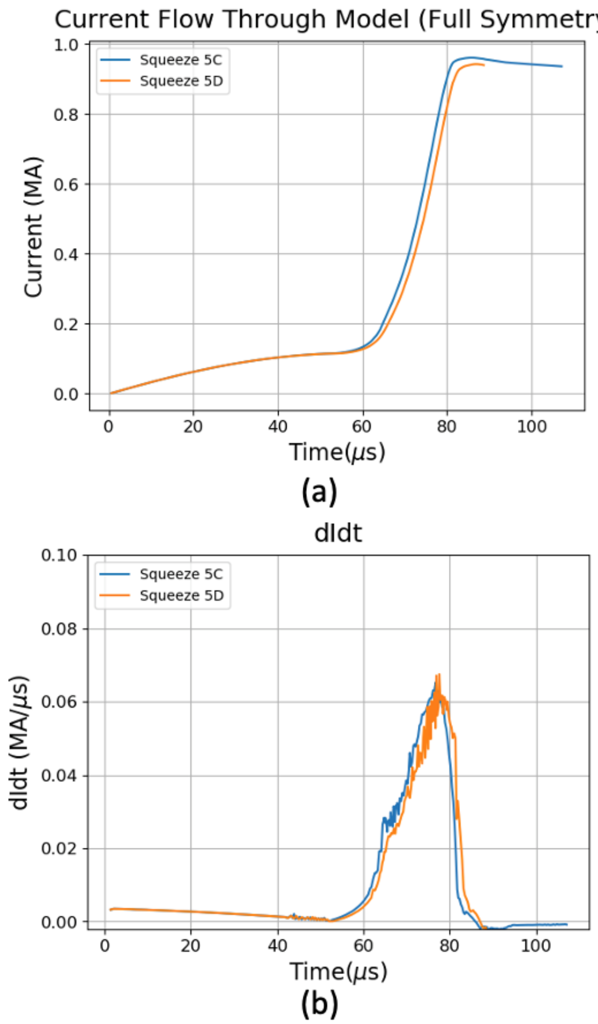

Fig. 8 Comparison of Squeeze 5C and 5D a) current and b) dI/dt

4. Design Problem Statement

The deformation of the stator (see Fig. 7) is caused by current density concentration as current exits the helical section of the generator. Energy is being used to heat up and accelerate material. Magnetic flux is being lost due to the motion resulting in a loss the efficient operation of the generator. In addition, the deformed slot may result in early shorting of the armature to stator gap, resulting in trapped flux. Minimizing the magnetic flux losses at the end of the coil is critical in eliminating losses in magnetic flux. In any FCG operation, a loss of magnetic flux will result in a lower output current.

To mitigate the design issues observed in Fig. 7, we decided to bifurcate the stator (coil) at the output end of the generator. The intention of this design is to allow current redistribution at the end of the FCG operation. Since the output of the generator has significant material motion and is being pushed to high temperatures, the redistribution of current will boost the output of the generator. The redistribution of current will decrease the effective resistance of the generator during the later stages of operation, resulting in less flux loss.

Figure 9 shows the geometry of the nominal and bifurcated coil. The nominal case includes one 6.35-mm (1/4-inch) variable pitch helical slot. The bifurcated coil has the same slot as the nominal coil but adds a second slot for the last two turns (half-way between the existing turns at the same pitch).

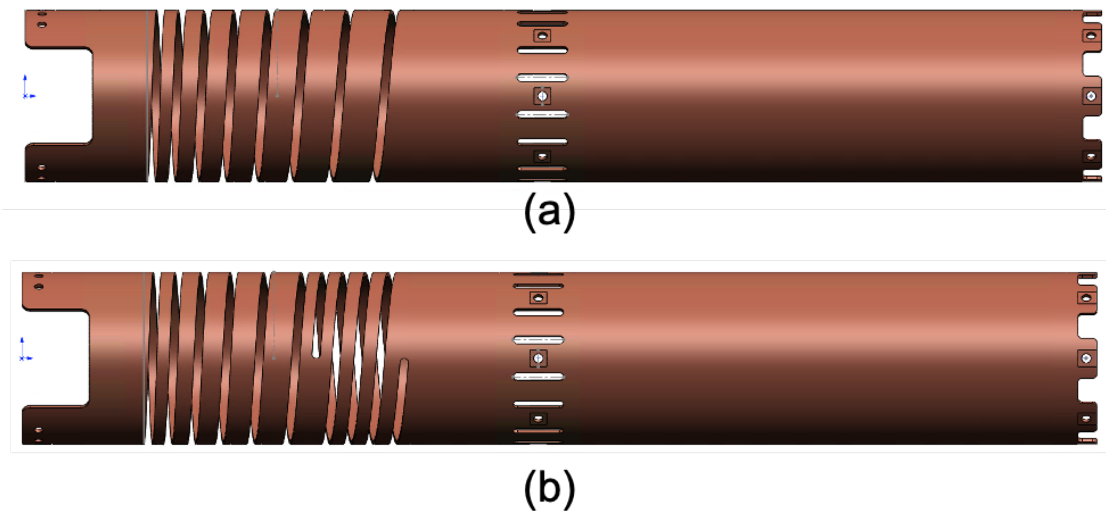

Fig. 9 Illustration of a) nominal coil geometry and b) bifurcated coil geometry

5. ALE3D-MHD Simulation Setup

Figure 10 shows the circuit network setup used in the ALE3D simulation. Details of the material models have been extensively reported in Vunni et al.[1–3] As in the previous simulation, the generator was driven with an RLC circuit seeded with a 110-kA current. The seed current was provided by an external circuit with seed 441-nH inductance, a 525-μF capacitor, an 8.5-mΩ resistance, and a charge voltage of 10 kV.[1,2]

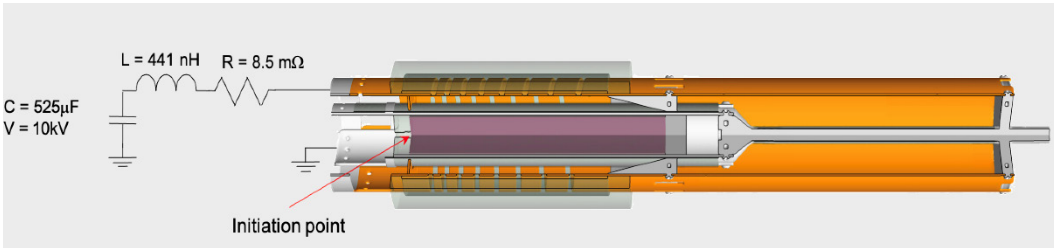

Fig. 10 ALE3D simulation setup showing external circuit connection to the FCG device

6. ALE3D-MHD Simulation Results

Figure 11 shows the current and dI/dt (I.dot) profiles from ALE3D-MHD simulations obtained from the bifurcated coils for both Squeeze 5C and 5D designs. The simulation predicts a maximum current of 1.04 MA for both designs for a seed current of 110 kA and a gain of approximately 9.0.

Figure 12 shows the plot of the dI/dt and current of the bifurcated geometry relative to nominal non-bifurcated Squeeze 5C. The bifurcated coil has a maximum current of 1.04 MA compared with the non-bifurcated output of 928 kA. The bifurcated case shows an overall current of 1.04 MA an increase of approximately 7%. It is believed most of this gain is due to the redistribution of the current causing a decrease in the effective resistance, although some may also be due to a slight increase in initial inductance of the generator. Further analysis is needed to differentiate between the two.

In Figure 13, the plots of dI/dt and the current output of the bifurcated coil of Squeeze 5D relative to the nominal coil are shown. The bifurcated case shows an overall increase of current of approximately8%. The dI/dt pulse is stretched out in time in the bifurcated pulse. Amplification is happening for longer because of less flux loss at the end of compression (which results in a higher current). It is possible that the lower losses of the bifurcated cases could allow higher seed currents to be used as well (up to some limit).

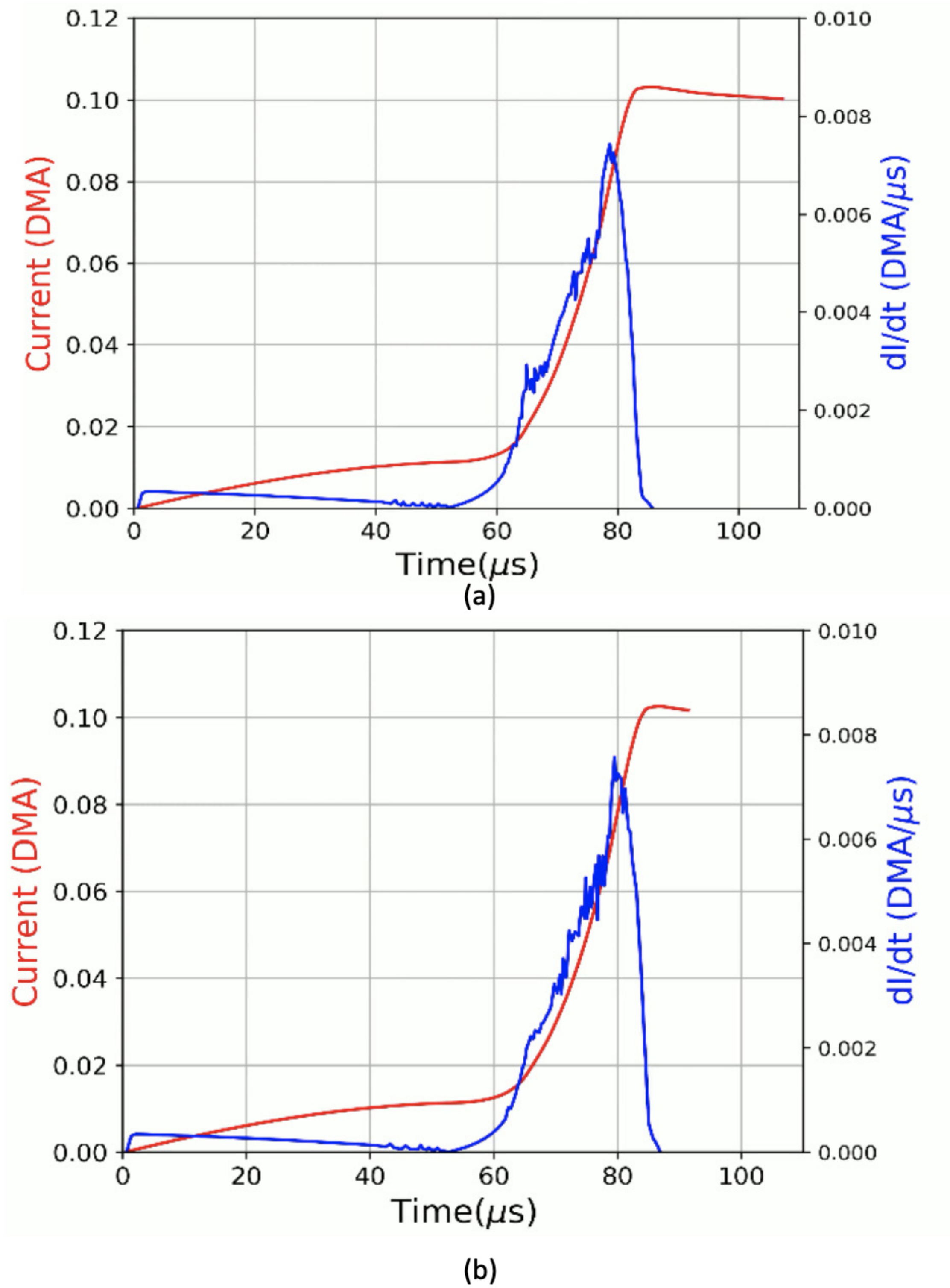

Fig. 11 Plots of dI/dt and current output for bifurcated a) Squeeze 5C and b) Squeeze 5D resulting in a current gain of 7% and 8% for seed current of 110 kA

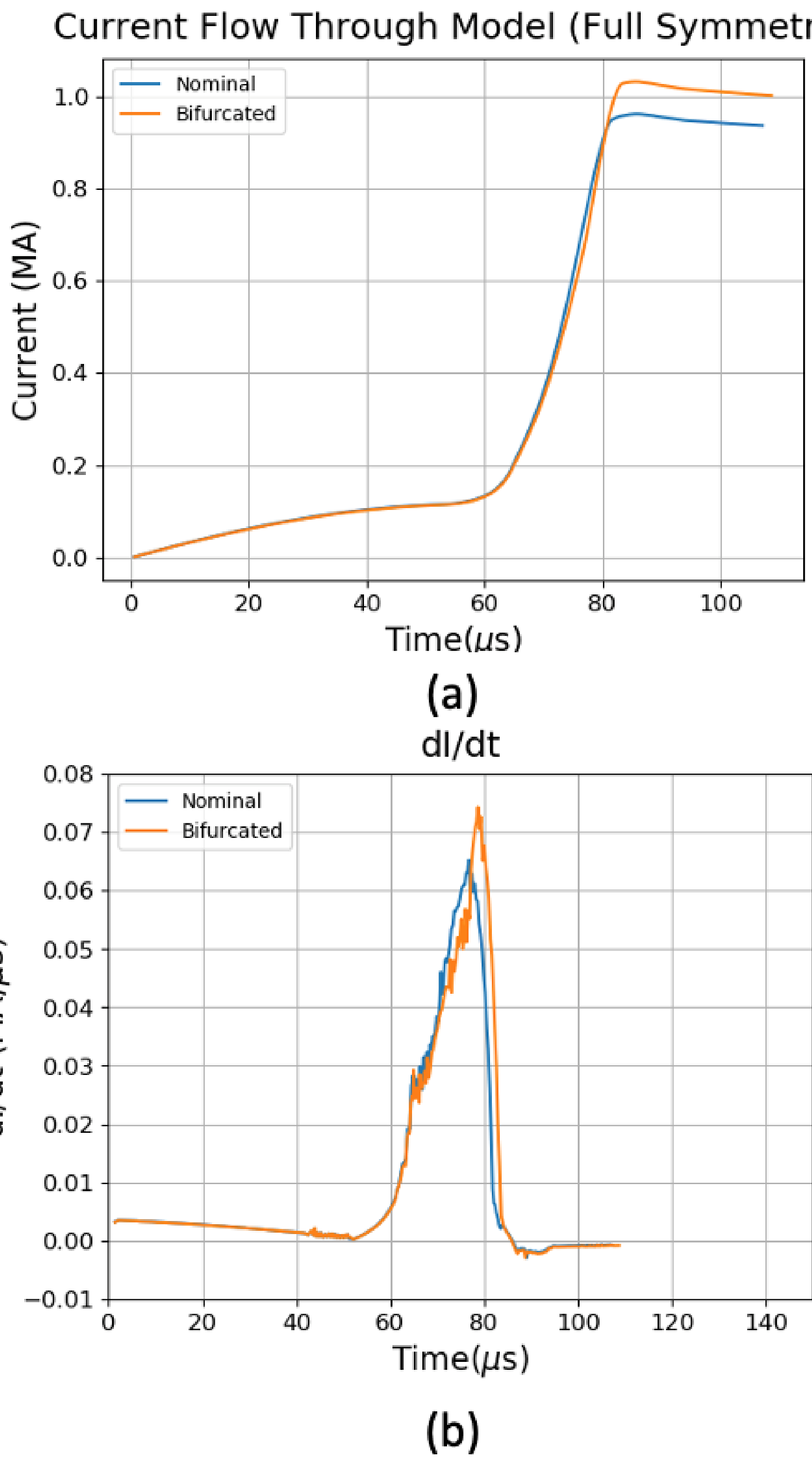

Fig. 12 Squeeze 5C: a) calculated current output comparison of bifurcated and non-bifurcated and b) dI/dt

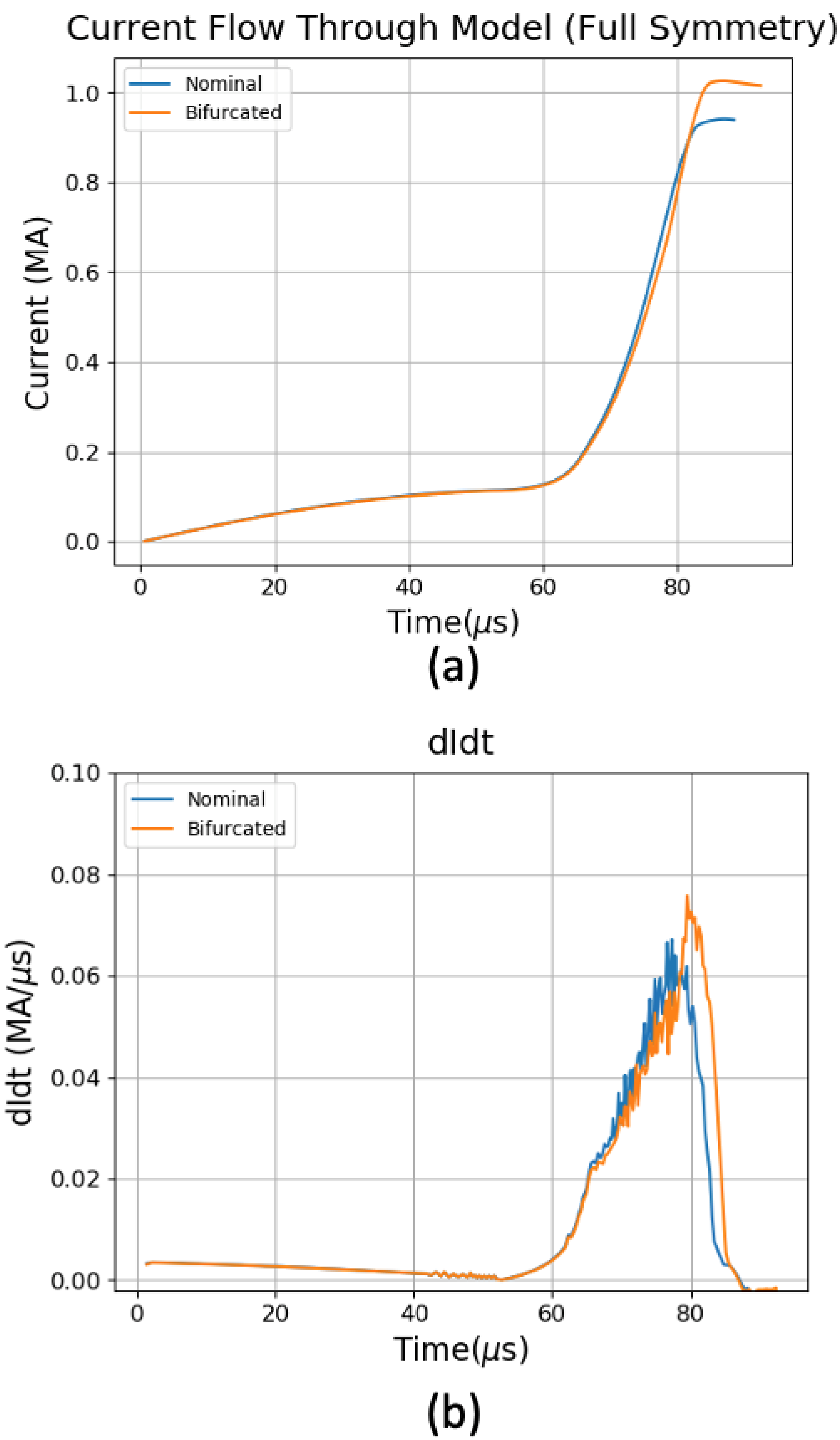

Fig. 13 Squeeze 5D: a) calculated current output comparison of bifurcated and non-bifurcated and b) dI/dt

7. Conclusion

We investigated the effect of stator (coil) bifurcation on the performance of two designs of ARL's Squeeze 5C and 5D FCG devices using ALE3D code. First, nominal, non-bifurcated cases were run and found to compare well with experimental data. These cases show significant heating and material motion near the output of the generator. The coils were then bifurcated to correct for this weakness in the original design and allow current redistribution near the output end of the generator. The goal was to reduce this excessive heating and material motion. The bifurcated coil simulation results for the Squeeze 5C and 5D show an increase in output current of between 7% and 8%, respectively, implying the design modification is worth pursuing experimentally. The authors speculate it may be possible to push to higher seed currents for both designs.

8. Future Work

In connection with future work, the following points will be considered:

- Run more varied seed-current cases to see if there is a maximum in this performance increase. It is expected that higher current cases may show better performance in the bifurcated case (up to some limit).
- Run more bifurcations at higher stress levels, which will require thinner slots. For Squeeze 5D, we plan to run a case with a longer cone section to alleviate the stress concentration at the helical slot.
- For Squeeze 5D, run a case with a longer cone section (work in progress).
- Run the current designs at higher seed currents.
- Built and experimentally test the new design (bifurcated coil).

We expect higher current cases to show better performance in the bifurcated case (up to some limit).

9. References

1. Vunni GB. The influence of coil winding gap and armature material on the performance of magnetic flux compression (MFC) Squeeze 5 device. CCDC Army Research Laboratory; 2019 May. Report No.: ARL-TR-8692.
2. Vunni G, Bartkowski P, Johnson A. ALE3D magneto-hydrodynamic (MHD) modeling of a new ARL Squeeze 5 magnetic flux compression generators. Army Research Laboratory (US); 2018 Sep. Report No.: ARL-TR-8505.
3. Vunni GB. Magneto-hydrodynamic simulations of a magnetic flux compression generator using ALE3D. Army Research Laboratory (US); 2017 July. Report No.: ARL-TR-8055.
4. Bartkowski P, Berning P. Design and testing of the ARL Squeeze 4 helical flux compression generator. Army Research Laboratory (US); 2013 June. Report No.: ARL-TR-6477.
5. Anderson A, Barton N, Biagas K. User manual for ALE3D, an arbitrary Lagrange Eulerian system, version 4.24. Lawrence Livermore National Laboratory; 2014 Sep 5.
6. Neuber AA, Dickens JC. Magnetic flux compression generators. Proceedings of IEEE. 2004;92(7):1205–1215.
7. Neuber AA. Explosive driven pulsed power: helical magnetic flux compression generators. Berlin (Germany): Springer; 2005.

List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	Army Research Laboratory
DEVCOM	US Army Combat Capabilities Development Command
dI/dt	time derivative
FCG	flux compression generator
MHD	magneto-hydrodynamic
RLC	Resistor Inductance capacitor

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