ARL-TR-8943 ● APR 2020

ALE3D-MHD Modeling of Modified Squeeze 5 Magnetic Flux Compression Generator (FCG) Device

by George B Vunni and Peter Bartkowski

Approved for public release; distribution is unlimited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

ARL-TR-8943 ● APR 2020

ALE3D-MHD Modeling of Modified Squeeze 5 Magnetic Flux Compression Generator (FCG) Design

George B Vunni and Peter Bartkowski
Weapons and Materials Research Directorate, CCDC Army Research Laboratory

Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED (From - To)
April 2020	Technical Report	30 September 2019–1 April 2020

4. TITLE AND SUBTITLE
ALE3D-MHD Modeling of Modified Squeeze 5 Magnetic Flux Compression Generator (FCG) Design

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
George B Vunni and Peter Bartkowski

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
CCDC Army Research Laboratory
ATTN: FCDD-RLW-PD
Aberdeen Proving Ground, MD 21005-5069

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-8943

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
ORCID ID: George Vunni, 0000-0002-7178-4899

14. ABSTRACT
The US Army Combat Capabilities Development Command Army Research Laboratory is actively working on an experimental program using a magnetic flux compression generator (FCG), called Squeeze, as a pulsed-power source for protection applications. The Squeeze FCG design is based on a cylindrical detonation system that expands the armature and delivers a current to a 160-nH load. The generator was designed to generate currents as high as 1.00 MA. Test results revealed a weakness in the design resulting in only 980 kA. The lower current amplification is caused by resistive and geometric losses in the design of the crowbar and glide-plane. The Squeeze 5 FCG was modified to correct this weakness and provide enhanced performance. In the new design, the crowbar and the glide plane are modified. This report focuses on the analysis of this modification using the Lawrence Livermore National Laboratory–developed magneto-hydrodynamic (MHD) code ALE3D. ALE3D-MHD simulation showed a 5% increase in current output of the modified Squeeze 5 generator.

15. SUBJECT TERMS
Squeeze 5, magnetic flux compression, coil winding, stator, ALE3D, MHD simulation, FCG

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					George B Vunni
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER (Include area code)
Unclassified	Unclassified	Unclassified	UU	22	410-278-8538

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

List of Tables

Acknowledgments

The author would like to thank Dr Anthony Johnson of Lawrence Livermore National Laboratory for lending his computational expertise and always being willing to have a technical discussion on modeling magnetic flux compression generators. Thanks to Dr Paul Berning and Mr Brian Krzewinski, Branch Chief, for the technical review.

This work was supported in part by a grant of computer time from the Department of Defense High Performance Computing Modernization Program at the US Army Combat Capabilities Development Command Army Research Laboratory Department of Defense Supercomputing Resource Center.

1. Introduction

Explosively driven magnetic flux compression generators (FCGs) are compact pulsed-power sources of current and voltage. The interest in such devices stems from their unique capability to achieve very high energy densities, magnetic field strengths, and high current pulses. In a typical FCG, a flux is established in a system of conductors arranged such that the magnetic flux is trapped. The system is explosively deformed to a smaller volume, thus compressing the magnetic flux and delivering electromagnetic energy into the connected load. Compression of the trapped magnetic flux amplifies the initial seed current (established by a small capacitor bank) injected into the coil. During this process, the inductance of the device rapidly decreases. In most FCG devices the energy density (i.e., the ratio of the electrical energy delivered to the load and the FCG volume) is typically a few joules per cubic centimeter.

The US Army Combat Capabilities Development Command Army Research Laboratory (CCDC ARL) has developed a family of FCGs called Squeeze used in explosively driven pulsed-power experiments. Our Squeeze 5 FCG can produce currents over 1.00 MA when seeded with 110 kA or greater.[1–4] The efficiency of an FCG is highly dependent on the expanding characteristics of the expanding armature and the nature of the contact between the armature and the surrounding stator (coil). The energy conversion process includes two steps: 1) primary energy of the high explosives to kinetic energy of the expanding armature and 2) the kinetic energy of the armature to the final electromagnetic energy. Previous simulations of the Squeeze 5 generator identified two pockets of trapped flux that can result in reduced performance. In an attempt to increase the inefficiency of the Squeeze 5 FCG design, modifications were made in the crowbar and the glide-plane designs. ALE3D-magneto-hydrodynamic (MHD) simulations were conducted to explore the performance of the modified Squeeze 5 FCG.

2. Brief Description of the Squeeze 5 FCG Device

Figure 1 shows a schematic cross section and a full 3-D image of the Squeeze 5 FCG device. The Squeeze 5 FCG device has been described in detail in Vunni[1] and Vunni et al.[2] In brief, the device has a C12200 copper coil (stator) with a 6063-TO aluminum armature. 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 copper 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 generator end. This increasing cross-sectional area of the conductor prevents coil melting or vaporization as the current builds in the device during its function.

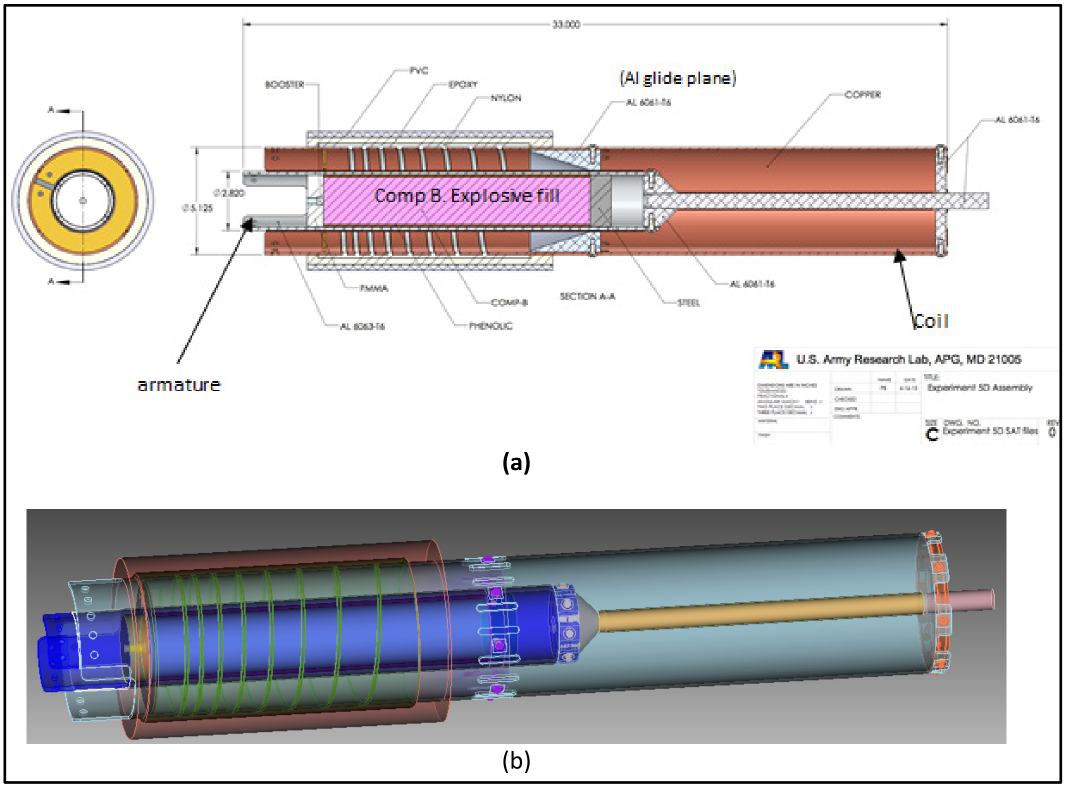


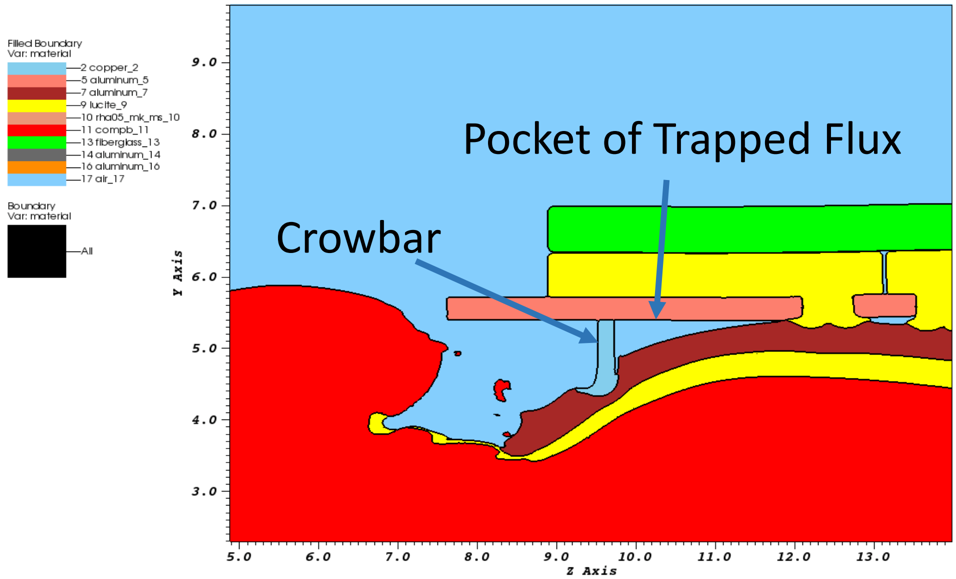
Fig. 1 ARL's Squeeze 5 FCG design: a) cross section and b) 3-D view

3. Design Problem Statement

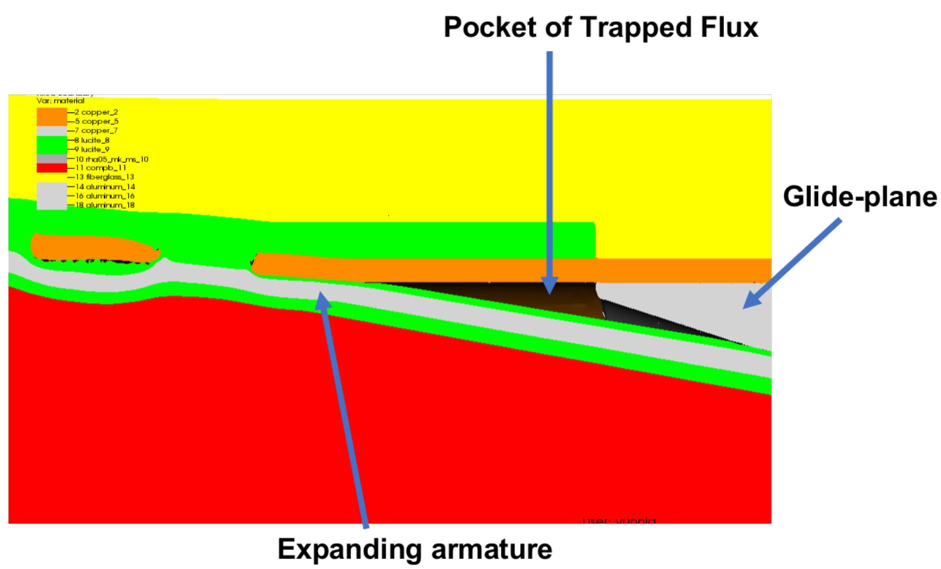
In previous ALE3D-MHD simulations of the Squeeze 5 generator,[1] we observed that a volume of flux was excluded from compression at the beginning and at the end of the compression. Figure 2 shows an illustration of trapped regions of uncompressed magnetic flux.

In Fig. 2a the armature expansion clearly shows the existence of an end effect,[5] 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 (Fig. 2a) is a coaxial field section;

however, a loss of a small amount of magnetic flux may influence the initial inductance of the generator. Previous simulation[1,2] has shown that the geometry of the crowbar is critical in eliminating the trapped magnetic flux.



(a)



(b)

Fig. 2 AL3D-MHD simulation illustrating gaps that resulted in trapped magnetic flux at the a) crowbar region at 60 μs (20 μs after detonation) and b) glide-plane region at 90 μs (60 μs after detonation)

Another region where magnetic flux is trapped is at the glide-plane, as shown in Fig. 2b, where a volume of flux is trapped at the initial slope of the glide-plane. Any volume of magnetic flux becomes trapped and impedes the reduction of inductance in the FCG, resulting in lower current output. This report focuses specifically on the effect of a redesigned crowbar and glide-plane on the simulated performance of the modified Squeeze 5 FCG device.

4. Squeeze 5 FCG Design Modification

In FCG design, flux loss mechanisms contribute to the physical limits of flux compression with respect to the performance and efficiency of the device.[5,6] Flaws in the FCG design can decrease the efficiency of the generator significantly. For example, a non-uniformly expanding armature can cause the contact between the armature and helix to jump in the worst case from turn to turn. In FCG operation, the moment of crowbar; where the seed current circuit is separated from the FCG, is important in reducing flux losses. If the crowbar is not carefully designed, a loss in the current or the value of initial inductance will be experienced. 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. It also needs to allow for a smooth and quick shorting-out of the source without any electrical arcing forming to avoid any loss of energy at the beginning of flux compression.

In order to address the design flaws shown in Fig. 2, two design changes were made to the Squeeze 5 FCG device. Fig. 3a shows the original crowbar design. The crowbar in the original Squeeze 5 FCG has a copper disk with 2.54-cm thickness. The modified crowbar (Fig. 3b) has a rounded edge with a glide-plane approximately 45°. The modified crowbar configuration has the advantage that the expansion armature makes a complete conduct with the stator (coil) eliminating trapped uncompressed pockets of magnetic field. The overall aim of this design improvement is to reduce flux loss through the compression time, thus maximizing the current gain.

Figure 4 shows the original and modified glide-plane. The original glide-plane (Fig. 4a) is 8.4 cm long with a glide angle of 18°. The modified glide-plane (Fig. 4b) is 1.8 cm longer with a reduced glide angle of 15°. The 15° glide angle is equal to the expansion angle of the armature observed in the original design.[2,3] A more detailed description of the armature expansion can be found in previous reports.[2,3] The reduction of the glide-plane angle serves to minimize pockets of trapped magnetic flux (Fig. 2b), resulting in a faster inductance reduction, and a higher current amplification.

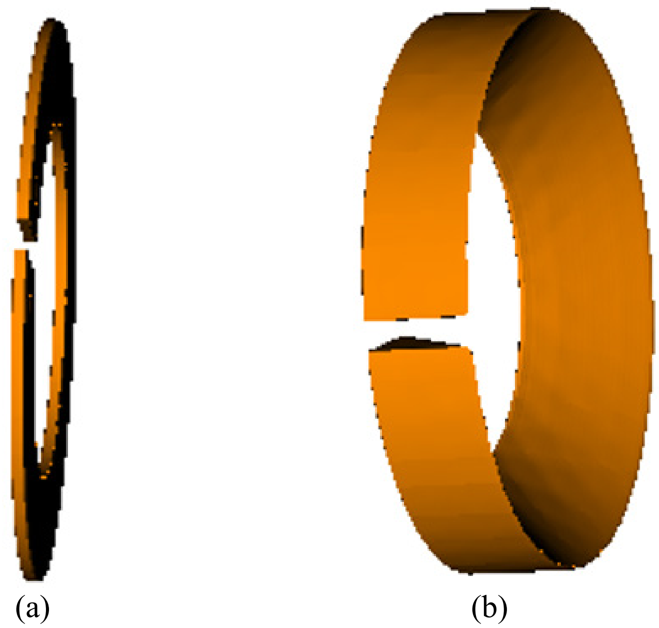


Fig. 3 a) Original and b) the modified crowbar ring

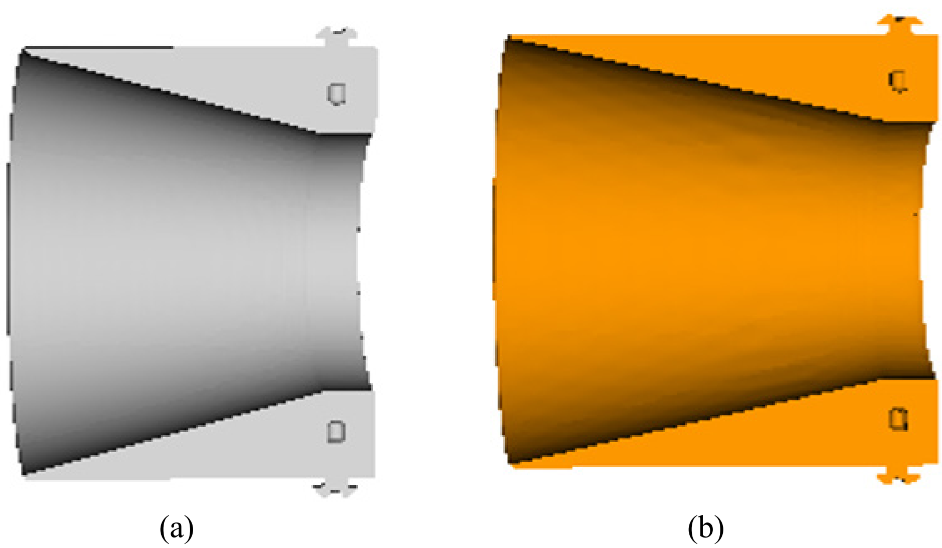
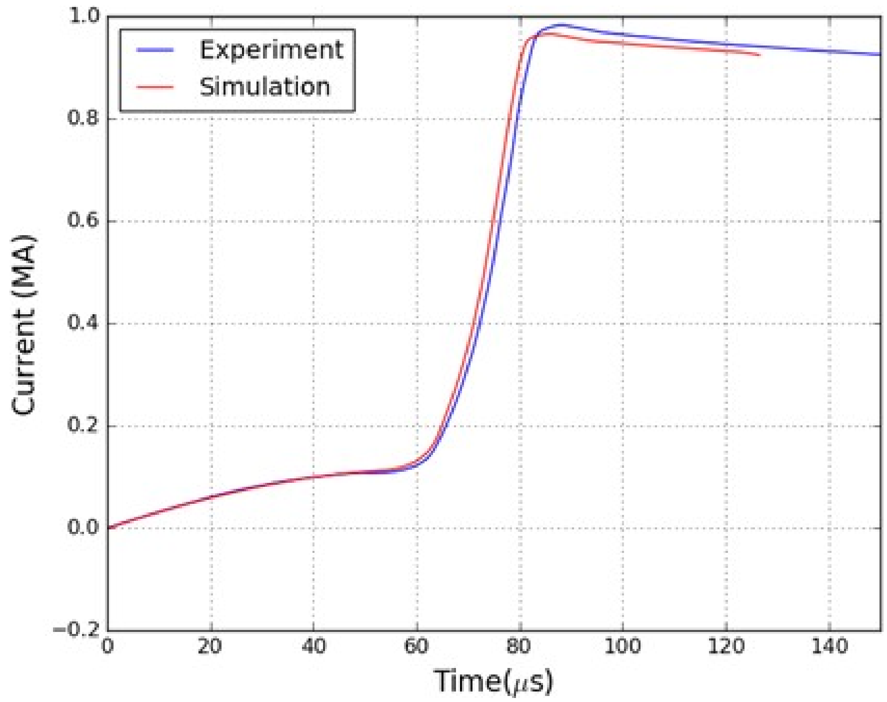
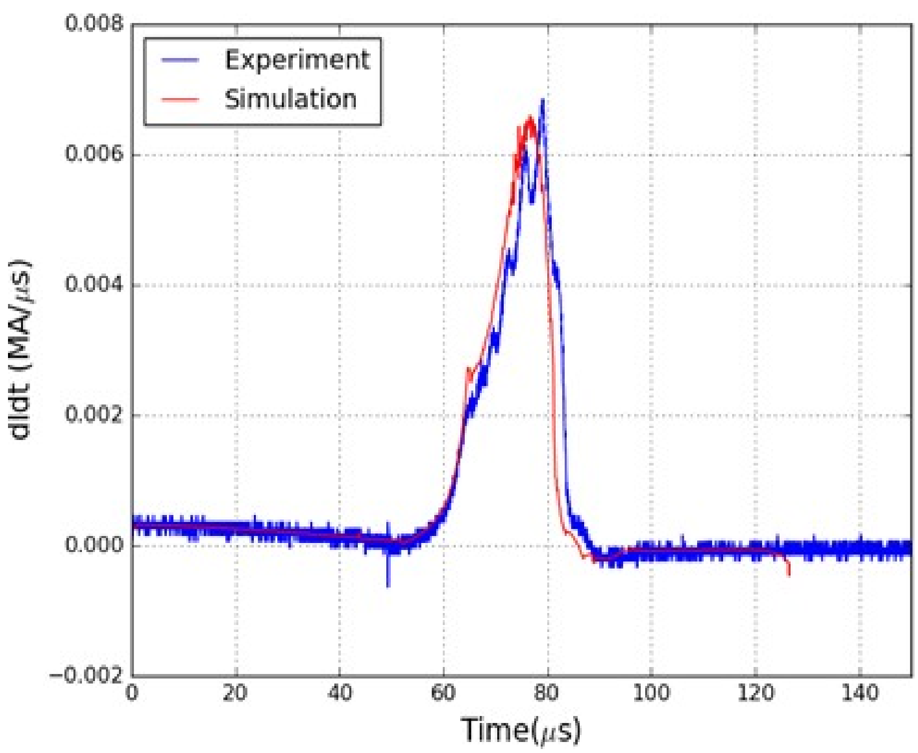


Fig. 4 A cutaway 3-D model of the a) original and the b) modified glide-plane

Figure 5 shows the plots of the simulation and measured current and dI/dt of the original Squeeze 5 FCG (with the original crowbar Fig. 3a and glide-plane Fig. 4a) design.[1] The result of the ALE3D-MHD simulation underpredicted the current gain by approximately 25 kA compared to the measured value. The measured maximum current was 0.980 MA compared to a simulated current of 0.955 MA.[1] One possible source for this difference could be the effect of uncompressed magnetic flux, which may result in low current output.



(a)



(b)

Fig. 5 Comparison of ALE3D-MHD simulation (red line) and experimental: a) current trace (blue line) and b) I.dot (dI/dt) of the original Squeeze 5 FCG for a seed current of 100 kA

5. ALE3D-MHD Simulation

5.1 Brief Description of the ALE3D Model

Simulation was performed using ALE3D-MHD code, a multiphysics numerical simulation software tool using arbitrary Lagrangian-Eulerian techniques developed by Lawrence Livermore National Laboratory.[7] ALE3D's MHD model is capable of capturing the dynamics of electrically conducting solids and fluids. The MHD module was developed primarily for the modeling of coupled electro-thermal-mechanical systems that are inherently 3-D in nature. Example applications for this capability include explosively driven FCGs, induction heating, metal forming, and electromagnetic rail gun systems.

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 H (Curl) and H (Div) finite element basis functions that preserve the solenoidal nature of the magnetic field to machine precision. Electromagnetic force and resistive Joule heating terms are coupled to the equations of motion and thermal diffusion in an operator split manner. For problems that require mesh relaxation, 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 as explained in detail in the ALE3D manual.[7]

5.2 ALE3D-MHD Simulation Setup

Full ALE3D-MHD simulation was conducted to investigate the performance of the modified FCG. Details of the simulation have been reported in Vunni et al.[1–3] The overall computational domain for this model is shown in Fig. 6a, including the materials. Figure 6b shows the seed current connection to the FCG device.[1–3] The conductors aluminum and copper were modeled using the SESAME conductivity model based on the modified Lee-More conductivity model.[8] The high explosive in the generator (Composition-B)[1] was modeled using the Jones-Wilkens-Lee model (line-of-sight lighting time). The detonation time was tuned to the crowbar at approximately the same time as in the original experiment. The generator was seeded with a 110-kA current. The seed current was provided by an external circuit with seed a 221-nH inductor, a 525-μF capacitor, and a 7.5-mΩ resistor.[1,2] In this simulation, the mesh consisted of approximately 21 million cells, and each run required about 200,000 CPU h to complete on ARL's high-performance computer system Excalibur.

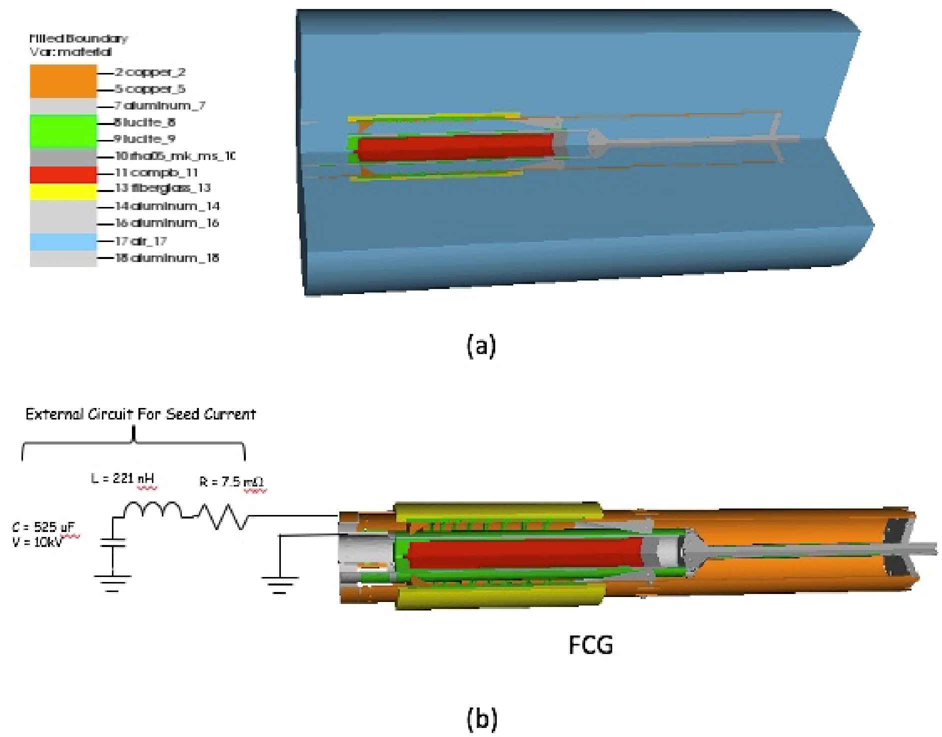


Fig. 6 ALE3D simulation setup showing a) mesh and materials and b) external circuit connection to the FCG device

6. ALE3D-MHD Simulation Results

The simulation was run with the experimental seed current input. The pulse is equivalent to a quarter-wave sine pulse with a peak of 110 kA. As previously described, the explosive was initiated such that the crowbar time corresponded to the experimental time reported in Vunni et al.[1,2] After the crowbar, the seed current is effectively isolated from the main compression circuit. The predictive capability of the code is being relied upon to calculate the current and dI/dt after this point. Figure 7 shows the expansion of the armature. The times at 60, 75, 85, and 90 µs occur after crowbar.

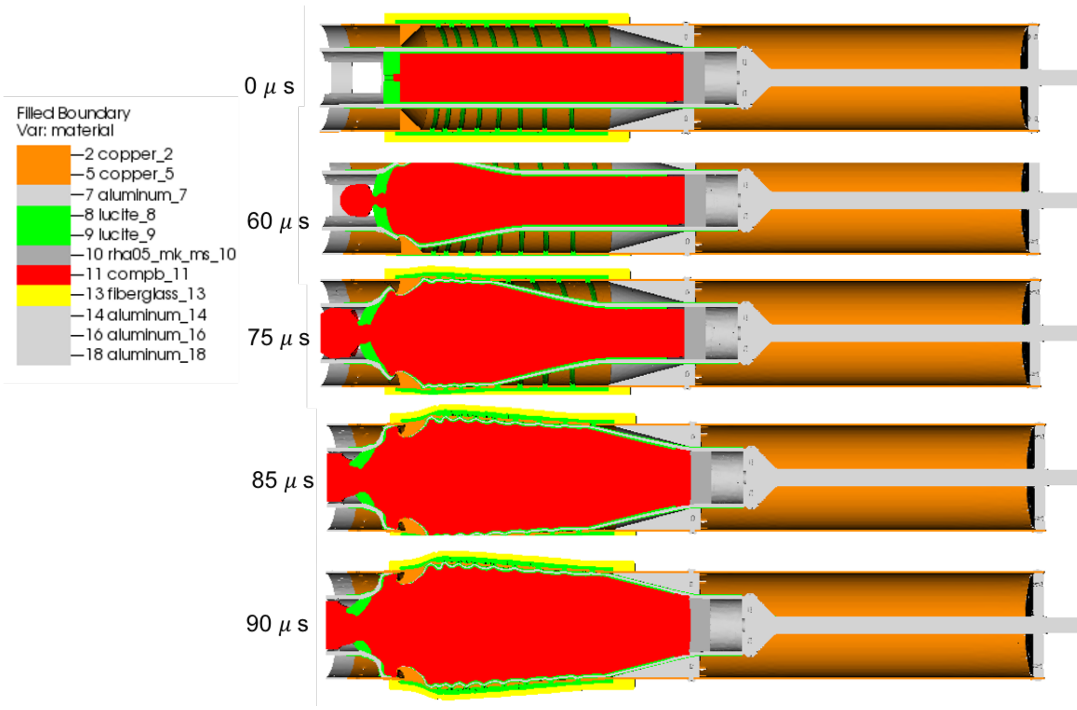


Fig. 7 ALE3D-MHD simulation of Squeeze 5 FCG. Shown are snapshots of the expanding armature (the times are simulation times).

Figures 8 and 9 illustrate the comparison of the armature interaction at the crowbar and glide-plane. The analysis of the modified design revealed that the crowbar and glide-plane design left no void, resulting in hardly any trapped pockets of magnetic flux. The loss of void reduces parasitic inductance to the system, thus increasing the output current.

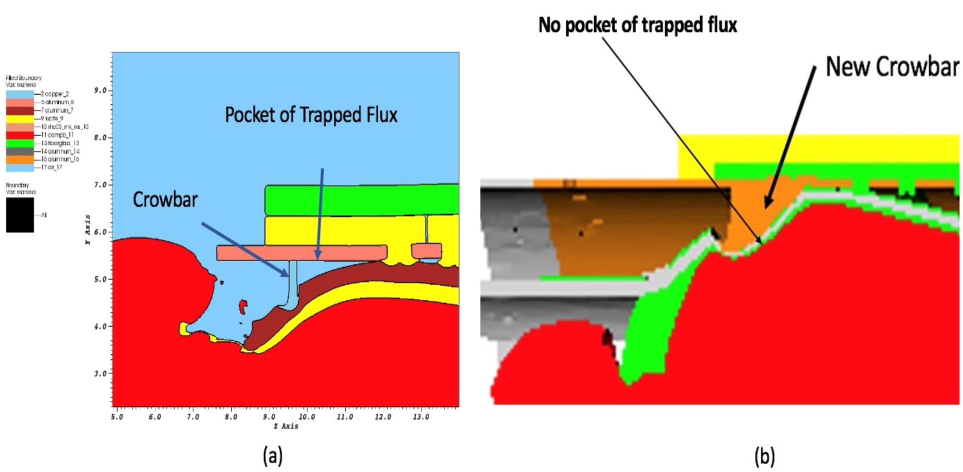


Fig. 8 Armature/stator interaction at the crowbar region: a) original and b) modified FCG design at 20 μs after detonation

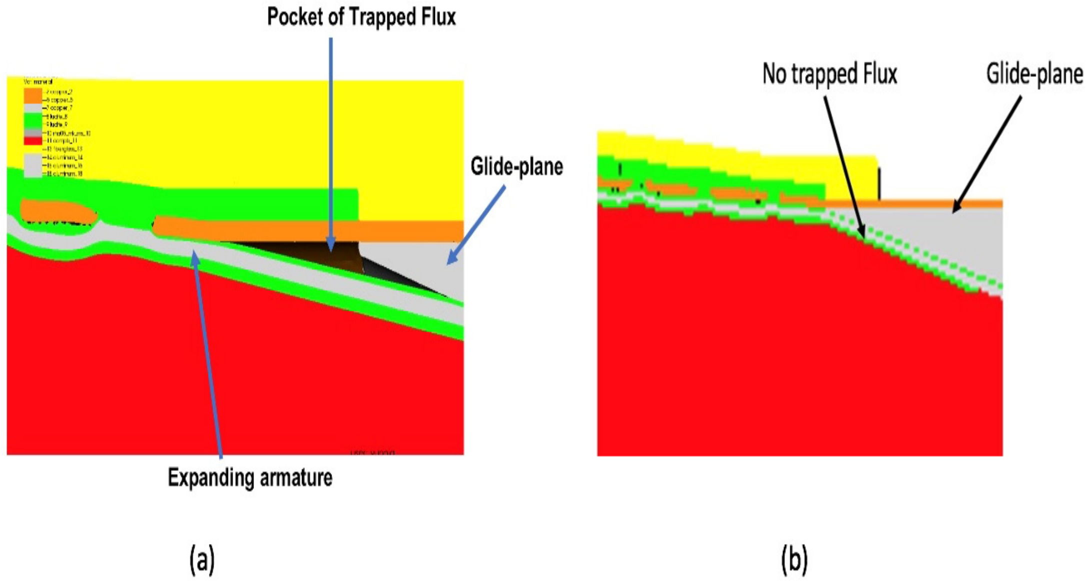
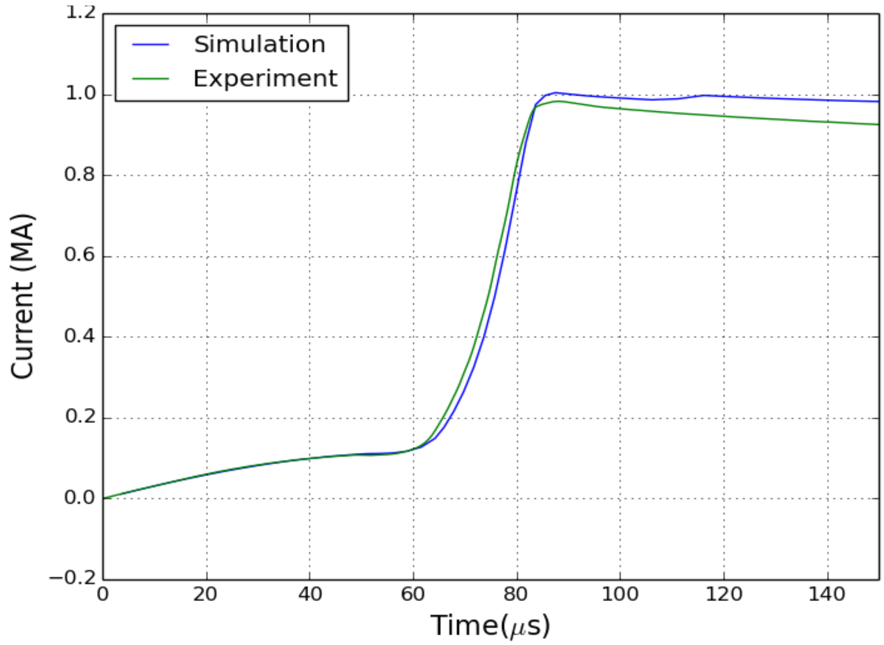
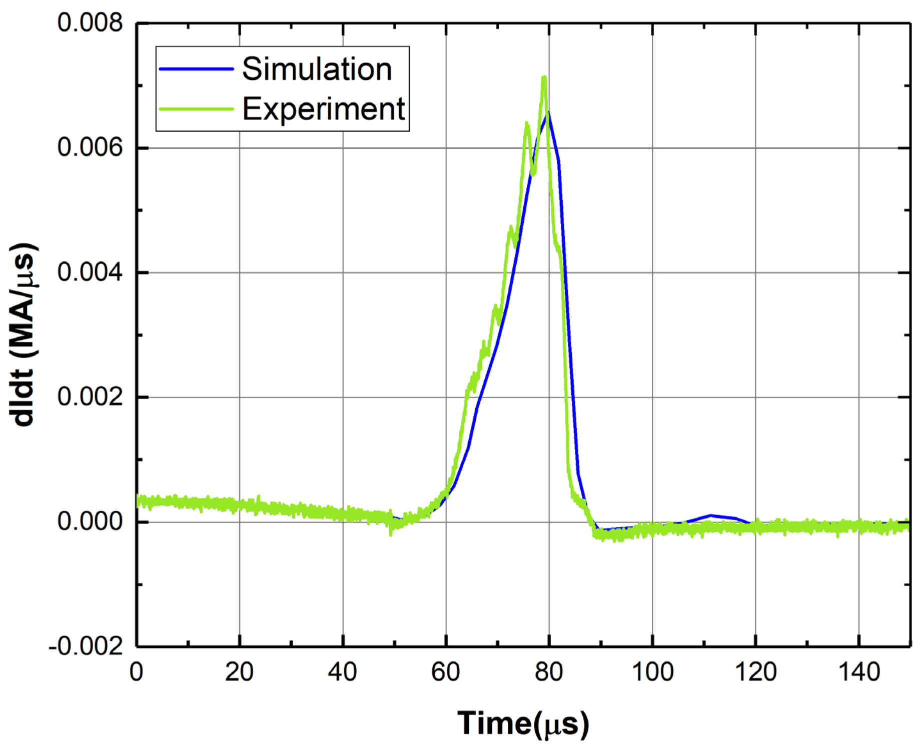


Fig. 9 Armature/stator interaction at the glide-plane region: a) original and b) modified FCG design at 90 μs

Figure 10 shows the plot of the current trace and dI/dt. The experimental data from the original Squeeze 5 device are included for comparison. The ALE3D simulation and experimental data are in good agreement. The current plot matches well for the first 60 μs (seed current) and then slightly overshoots the experimental current compression that begins at approximately 80 μs. The simulation predicted a maximum current of 1.030 MA, which differed from the experimental peak current of 0.980 MA by approximately 50 kA. In the modified design, the simulation slightly overpredicted the gain at the end of the generator operation (approximately 85 μs, Fig. 10a). The increase in the compressed current indicates that the magnetic flux loss near the crowbar and at the glide-plane has contributed to the increased gain of the FCG device. A summary of the peak current, and initial and final inductance is given in Table 1.



(a)



(b)

Fig. 10 Plot of ALE3D simulation a) current output (blue) and b) dI/dt of the modified FCG for 110-kA seed current. The original current and dI/dt are plotted for comparison.

Table 1 Performance summary of the modified FCG results compared to the original FCG

Parameters	Original FCG	Modified FCG
Seed current	110 kA	110 kA
Peak experiment current	0.980 MA	. . .
Peak simulation current	0.955 MA	1.030 MA
Initial inductance (L_I) sim.	2445 nH	2449 nH
Final inductance (L_f) sim.	230 nH	135 nH
Initial inductance (L_I) exp.	2440 nH	. . .
Final inductance (L_f) exp.	155 nH	. . .

7. Conclusion

Large magnetic flux losses due to uncompressed flux can dramatically decrease the efficiency of an FCG device. In this report, the effect of crowbar and glide-plane modification on the output of the Squeeze 5 FCG was computationally investigated using the ALE3D-MHD code. In an effort to increase the current gain, the new design corrects two small areas of the internal geometry of the original design. The result of the simulation is compared to the original Squeeze 5 FCG design and the one experiment. For the original Squeeze 5 design, the maximum simulated current output was 955 kA, slightly lower than the 980 kA observed experimentally. For the modified design, the simulated current output was 1030 kA (1.030 MA), a 5% increase from the original design. The increase in current gain due to the design change provides a sound basis for additional experimental testing. The result of the modified design shows that ALE3D-MHD code provides an extremely powerful tool for use both in designing FCGs and improving the performance of an existing design.

8. References

1. Vunni GB. The influence of coil winding gap and armature material on the performance of magnetic flux compression (MFC) Squeeze 5 device. Aberdeen Proving Ground (MD): CCDC Army Research Laboratory; 2019 May. Report No.: ARL-TR-8692.

2. Vunni GB, Johnson A, Bartkowski P. ALE3D magneto-hydrodynamic (MHD) modeling of a new ARL Squeeze 5 magnetic flux compression generator. Aberdeen Proving Ground (MD): 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. Aberdeen Proving Ground (MD): 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. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2013 June. Report No.: ARL-TR-6477.

5. Neuber AA. Explosive driven pulsed power: helical magnetic flux compression generators. Berlin (Germany): Springer; 2005.

6. Neuber AA, Dickens JC. Magnetic flux compression generators. Proceedings of IEEE. 2004;92(7):1205–1215.

7. Anderson A, Barton N, Biagas K. User manual for ALE3D, an arbitrary Lagrange Eulerian system, version 4.24. Livermore (CA): Lawrence Livermore National Laboratory; 2014 Sep 5.

8. Desjarlais MP. Practical improvements to the Lee-More conductivity near the metal-insulator transition. Contributions to Plasma Physics. 2001;41:267–270.

List of Symbols, Abbreviations, and Acronyms

3-D	3-dimensional
ARL	Army Research Laboratory
CCDC	US Army Combat Capabilities Development Command
FCG	flux compression generator
MHD	magneto-hydrodynamic

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
1 (PDF)	CCDC ARL FCDD RLD CL TECH LIB
1 (PDF)	SNL J NIEDERHAUS
20 (PDF)	CCDC ARL FCDD-RLW C P BARTKOWSKI FCDD RLW PA P BERNING C UHLIG M COPPINGER J FLENIKEN FCDD RLW PD G VUNNI R DONEY S SCHRAML D KLEPONIS D KEELE C RANDOW F MURPHY B KRZEWINSKI S BOYER M ZELLNER FCDD RLW PE D HORNBAKER M LOVE P SWOBODA J HOUSKAMP C KRAUTHAUSER