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Optimization and Critical Design Issues of the Air Core Compulsator for the Cannon Caliber Electromagnetic Launcher System (CCEML)

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Abstract -- **The Center for Electromechanics at The University of Texas at Austin (CEM-UT) is nearing completion of the manufacturing phase of a mobile platform, compulsator (CPA) driven 30 mm (round bore equivalent) rapid fire railgun system. The system has been designed to deliver 15, 185 g integrated launch packages at 1850 m/s muzzle velocity, using a series of three, five round salvos, and be compatible for integration into the amphibious assault vehicle (AAV). This paper describes the results of the optimization process used in determining the power supply requirements for the CCEML. The paper also presents predicted performance specifications which are based upon an end to end system simulator, a brief overview of the CPA design, and critical engineering design issues in the CPA which have been resolved along the way to reduce risk for the CCEML program.**

INTRODUCTION

The team of (prime contractor) FMC-NSD and (sub-contractors) CEM-UT and KAMAN Sciences Corp. (KSC) is currently nearing the end of the manufacturing phase of a 36 month effort to design, build, and test an electromagnetic (EM) launcher technology demonstrator (TD) with program goals as summarized in table 1. A very unique aspect of this particular program was that desired penetrator rod (subprojectile) performance at the target was specified; no specifics relative to EM power supplies or system configurations were given. Defining the optimum system required an intensive tradeoff study which looked at nearly all facets of the current EML state of the art in power supplies and launchers. The results showed a four-pole, self-excited, field regenerative, selective passive air-core compulsator (CPA) design to be the best power supply to satisfy contractual goals.

The four-pole CPA design was optimized around five independent parameters including launch package mass, muzzle velocity, pulse width, and number of shots stored inertially in the rotor. The overall system optimum configuration settled on launching 15, 185 g launch packages (95 g subprojectile mass) in three, five-shot salvos with a muzzle velocity of 1850 m/s. Performance was defined in detail by developing an end to end digital simulator of the system. This simulator includes the prime mover, drive train components, and detailed algorithms defining the nonlinear characteristics of the CPA, bus, and series augmented launcher.

Efforts have been intensely focused on reducing risk in the CCEML design, and our results and conclusions have been reviewed by a panel of EM gun technology experts assembled by the U.S. Government. The panel made several useful technical recommendations for the design team to follow in order to reduce overall system risk and found no fatal flaws or any specific technical show stoppers for the CCEML project.

Table 1. CCEML SOW requirements

Parameter	SOW Requirement	Current Design
Armor Penetration 0° and (56°) obliquity	73 mm (131 mm) RHA @ 1,500 m 37 mm (66 mm) RHA @ 3,000 m	meets spec
Caliber	20 to 40 mm	30 mm (equiv)
Firing Rate	300 to 400 rounds per minute	300
Salvo Size	5 to 7 rounds (3 salvos total)	5
Time Between Salvos	2 - 2.5 s	2.5
Probability of Hit	0.9	0.9 (planned)
System Weight	5,000 lb maximum	6100 lb
Weapon Mounting Platform	Compatible with AAV	meets spec

CPA PERFORMANCE AND OPTIMIZATION

Optimization of the Compulsator for the Cannon Caliber System

Specification of penetration goals on target allowed the design team to look at some broader, system wide tradeoffs since the launch package mass and the velocity at the muzzle were flexible parameters. The system optimization considered specific issues such as dispersions at the muzzle and the probability of hit in order to determine the optimal shots per salvo and salvos per mission.

The logical starting point in the optimization was the design of the subprojectile, since each subprojectile had to meet the penetration requirements at the target. Three different penetrator nose tip radii were considered for five muzzle velocities, which ranged from 1.7 km/s to 2.3 km/s in increments of 150 m/s. For each velocity/nose tip a projectile was designed with the appropriate aeroballistic and penetration characteristics. Three pulse widths (1.4, 1.7, and 2.0 ms) with the same average-to-peak acceleration (acceleration ratio) of 0.5 were considered, basically implying three peak accelerations. It was determined that the mid-drive penetrator was

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not significantly different for the three peak acceleration designs. However the tandem armature was affected by the peak acceleration issues. This resulted in a total of 45 different integrated launch package (ILP) designs with corresponding muzzle kinetic energy requirements. For each of the ILPs an optimized launcher was designed. In this case optimum was defined as a barrel/ILP package combination that resulted in a minimum breech energy requirement. An interesting tradeoff arises in the selection of the type of launcher.

Augmented vs. Simple Railgun

In any launcher the useful energy is that which is imparted to the payload. All other energy (including the kinetic energy in the armature) represents a loss. An augmented launcher typically has extra losses associated with the augmenting turn, with the result that if the muzzle energy of the launch package was fixed it would indicate a higher breech energy requirement. However with an augmented launcher the action ($\int i^2dt$) through the armature is lower with the result that the armature can be lighter thus resulting in lower muzzle energy requirements. It is therefore conceivable that the breech energy requirements in the augmented launcher be lower than a simple launcher. This has been our observation on the CCEML system which finally led to the selection of the augmented launcher.

Energy Storage

The pulsed power and energy storage system selected for the CCEML is the compulsator (CPA). Size and weight issues are driven to a large extent by the manner in which energy is apportioned between the prime power and the pulsed power. Considering that the time between salvos is only 0.2 s for a 300 rpm firing rate, it is evident that enough kinetic energy needs to be stored in the rotor to complete one salvo. The time between salvos is 2 to 2.5 s so recharging between salvos requires lower power than recharging between shots, however, it is still relatively high. To conduct an effective tradeoff study CPAs were designed to store one, two and three salvos with five, six, and seven shots per salvo (i.e. a total of nine machines for each barrel/launch package combination). The total number of CPAs thus designed were 45 x 9 = 405. Figure 1 summarizes the results of the optimization process. The CPA mass is most sensitive to the energy stored in the rotor. Typically it shows a lower mass increment for higher energy storage because given that the rotational speed is governed by pulse width considerations more energy storage means higher tip speeds thus higher energy density. Over the range of parameters considered the sensitivity of the CPA mass to projectile velocity, pulse width and nose tip radius is not significant. For a given energy storage the various machines fell within a 100 kg window. Probability of hit considerations required a total of three salvos and five shots per salvo at 300 rpm. Considering integration issues it was decided that the CPA store enough energy to complete all 15 shots without remotoring.

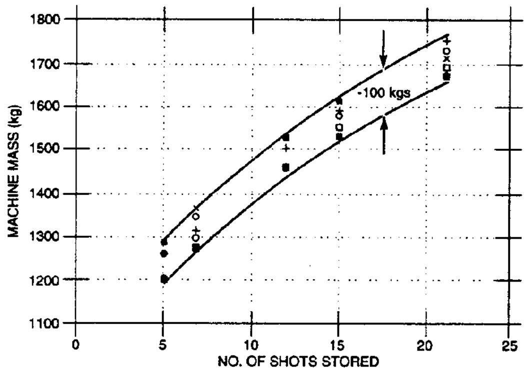

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Figure 1. Summary of machines investigated

Pulse Shape

Three pulse shapes were considered as shown in figure 2. The common feature in these pulse shapes is that each one has the same peak current and each have the same action. These pulse shapes are obtained with the passive, selective passive and the staged discharge machines. The acceleration ratio with the passive machine is about 0.38 and the other machines have a ratio of between 0.5 to 0.6. The staged discharge CPA is at present an unproven concept and to minimize risk on this project was not pursued. Of the other two pulse shapes the selective passive CPA which has a better acceleration ratio also has a shorter pulse width. This indicates that the CPA can spin faster and has a higher energy density. Thus there is a correlation between the pulse shape and the energy density which resulted in the selection of the selective passive CPA.

Number of Poles

To get the longest pulse width at the highest tip speed (and highest energy density), it is necessary to keep the number of poles to a minimum. This is especially true of the single phase variant of the CPA. When energy limited systems are being considered energy density needs to be maximized

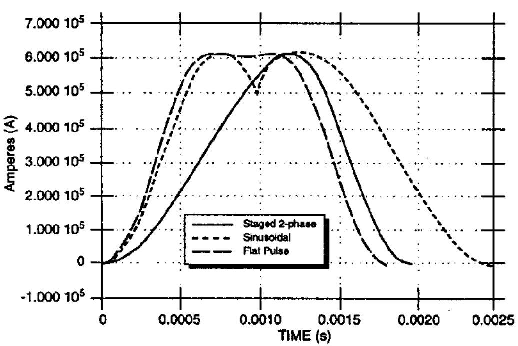

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Figure 2. Comparison of various pulse shapes

which normally results in the selection of a two pole machine. However there are some difficulties with a two pole design. The shaft of the rotor would have to spin in a high magnetic field with a two pole design. Using a conductive shaft material causes severe eddy currents. This results in two options neither of which are desirable. One is to use a ceramic shaft and the other is to use a copper clad Inconel™ shaft. In the latter option the copper which acts as a shield would have to be actively cooled.

The force distribution in a two pole CPA is non-uniform during discharge. The center of force on the two pole windings is at diametrically opposite points, leading to higher stresses. The non-uniformity of pressure results in local bending which adds to the hoop stress. Also, it is difficult to manage the deflections under the non-uniform loading especially when the clearances between stationary and rotating parts need to be at a minimum.

With the four pole CPA the field strength reduces at distances away from the field winding towards the center, until at the center the field strength is zero. This permits the use of a conductive shaft which does incur much lower levels of eddy current losses. Also the four pole winding has the center of force distributed at four equidistant points along the circumference which leads to a more even load distribution. Considering these and other advantages the four pole geometry was selected.

Performance of the System

In a typical operating mode the CPA will be driven by a frequency controlled, direct drive 450 hp induction motor to a top speed of 12,000 rpm. After reaching the top speed the discharge sequence will commence. A typical shot has three distinct events. In the first 80 ms the field coil is charged in a self-excitation mode. To initiate this process a capacitor is first discharged into the field coil which provides the seed current. When the appropriate CPA voltage is reached, current is commutated into the launcher over 2 ms. Over the next 90 ms part of the magnetic energy stored in the field coil is recovered and returned to the rotor. The motor drives the CPA at full power throughout the discharge cycle, but is protected from large deceleration transients by a slip clutch. After the discharge is complete the motor resynchronizes with the rotor in about 15 ms. In this manner energy is being delivered to the rotor at a steady rate throughout the mission.

Peak current in the launcher ranges from 835 kA for the first shot to 695 kA in the last shot. The launch package muzzle energy remains the same for all shots. Figure 3 shows the 15 current pulses during a machine. Figure 4 shows variation in the machine speed over the machine. A little over 50% of the energy is used over the mission. The majority of the shots take place without a muzzle arc. However since the machine does slow down to about 70% of its original speed over the mission the last few shots need a muzzle switch to suppress the muzzle arc. This ensures that the projectile has minimal dispersion at exit.

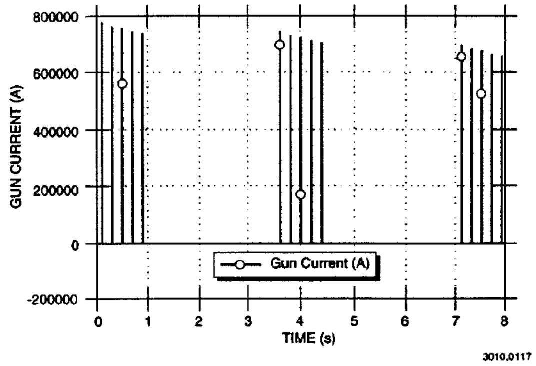


Figure 3. CCEML gun current during a mission

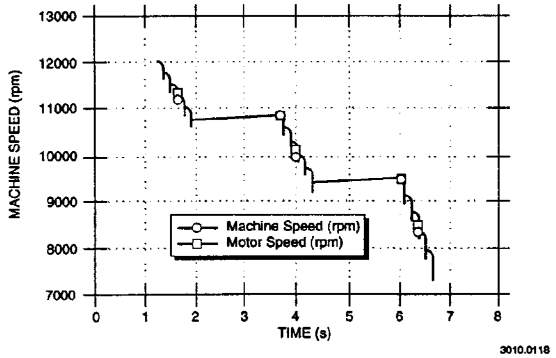


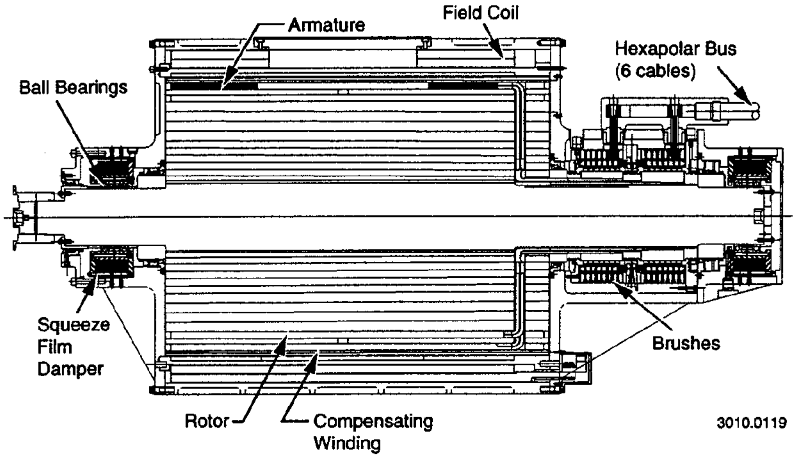
Figure 4. CCEML machine and motor speed during a mission

An end-to-end simulation code was developed to predict the performance of the system. The simulation includes the motoring, clutch characteristics, compulsator performance with the launcher, the armature and the muzzle switch. All aspects such temperature and speed effects are fully included. This detailed simulation is essential when a system is optimized to store the minimum amount of energy thus minimizing the mass of the machine and all the components.

Compulsator Design Overview

CPA Topography and Specifications

Reference 1 is a paper from the 1993 Pulsed Power Conference which talks in more detail to the design of the CPA. The CPA is a four-pole, air-core, selective-passive design which is self-excited and regenerates field energy between each shot. Figure 5 shows the longitudinal cross section of the compulsator. The CCEML CPA has been strongly influenced by the most attractive features found in previous designs including the Task-C range gun and Small Caliber Compulsator systems [2,3,4]. The CCEML CPA structure is formed using four, Ti 6Al-4V castings. The composite rotor is supported on hybrid ceramic rolling element bearings which are suspended in special squeeze film damper cartridges. The entire bearing set for the generator requires



Figue 5. Four pole, air core CPA layout

only 4 gpm lubricant flowrate. Great emphasis was placed on minimizing the CPA weight which makes up for about 80% of the entire system weight.

The following sections concentrate on the most critical issues concerning the design of the CCEML CPA. The contents will give the reader some insight on what is most important concerning the design of present technology air-core compulsators.

Rotor

Energy storage for the cannon caliber compulsator power supply is provided by a titanium shaft, composite flywheel assembly, four pole aluminum litz wire armature winding, and high strength, high modulus composite banding. The single rotor armature winding has the dual role of providing field coil current and the main railgun driving current.

The most critical issues governing the rotor design included composite material selection, fabrication, banding assembly, and the transition region at the end of the rotor where litz wire conductors are crimped into the solid copper coax which carries both field and discharge currents in and out of the CPA.

Table 2. CCEML CPA performance parameters

Operating speed range	12,000-8,400	rpm
Energy storage	40	MJ
Peak field	2	T
Peak open circuit voltage	3.84	kV
Peak design current`	835	kA
Peak power	2.6	GW
Discharge torque	2.0	MN-m
Peak electrical freq.	400	Hz
Nominal pulse width	2	ms
Action (15 shots)	9.15	GA^2-s
Stored energy dens	19.3	J/g
Specific energy dens	47.6	MJ/m^3
Power density	1160	W/g
Del. energy dens. (15 shots)	4.35	J/g

IM7 graphite towpreg and S2-glass towpreg composite cylinders are used extensively throughout the rotor for layer construction. The use of towpregs is presently advocated over wet wound cylinders due primarily to the availability of toughened resin systems. The number of layers required is based on the maximum allowable wall thickness which is a function of many factors which affect the residual fiber stresses and ply waviness. Since fabrication and assembly of each layer requires a substantial amount of tooling, this area is open to further development which could lead to reduced costs for volume production.

At 12,000 rpm, the armature poles develop high centrifugal loads which are resisted by a graphite composite banding. Banding material selection and minimum thickness is driven by the allowable stresses and radial growth induced during rotation and discharge, while the maximum thickness is limited by performance reductions from increasing the physical airgap between the field coils and armature/excitation windings (i.e. reduced coupling). Finally, to reduce assembly risks, it is desirable to have initial engagement between the banding and tapered armature surface prior to applying axial assembly force. The current banding design uses an IM7 banding with a 0.114 in. radial interference. This material has consistently demonstrated strengths in excess of 400 ksi in CEM-UT's split-D fixture. Stress levels anticipated for the CPA banding are below 200 ksi.

One of the most difficult design aspect for spinning armature CPAs is containment of the potted conductors which are routed down the rotor face and eventually transition to the slip rings. After vacuum impregnation, the potted conductors are bonded to the flywheel surface so that radial loads in the end conductors are transmitted by bond shear stresses. To give added support, a set of nested rings (identical in construction to the flywheel layers) is assembled and bonded to the outer face of the potted conductors. Consideration is also given to the possibility of crack propagation along the bond lines at these interfaces by allowing certain layers of the flywheel end end ring assemblies to penetrate into the face conductor region. In addition to providing mechanical keying, axial plies in the flywheel and end ring layers tabs serve as crack arrestors, should one develop on the face.

Bearings, Dampers, Rotordynamic Issues

The primary design criteria in this regard was that the operation of the CPA rotor not be adversely affected by shaft vibration. This means that the rotor must be well balanced, and free of lightly damped resonances in the operating speed range. Despite the high stiffness and low weight of the composite bands, the rotor is too flexible to run subcritical. This, combined with the fact that the demands of the application require the use of rolling element bearings which are inherently lightly damped, dictates the use of separate bearing dampers. To this end, the support ball bearings are housed within specially designed squeeze film damper (SFD) elements designed by the KMC Corp. The stiffness and damping properties of the SFD's were optimized via a damped rotordynamic analysis to place the "rigid rotor" critical speeds safely below the 8,000 rpm minimum design speed, and also to be well damped to allow their safe traversal. Significant bending of the rotor occurs only at speeds well above the 12,000 rpm maximum design speed. Thus, the CPA rotor should run smoothly up to and throughout its entire operating speed range.

Compensating Winding

By virtue of its electrical angle between the field and armature windings, the selective-passive compensating winding (CW) shapes the CPA discharge pulse. Varying this angle taylors the internal impedance of the CPA allowing for customized pulse shapes. A significant penalty for this, however, lies in charging efficiency for the field winding. At any angle off of electrical quadrature, the shorted turns of the CW have currents induced in them while the field ramps up. These currents produce fields which act to keep the magnetic flux out the CPA, and ultimately lead to longer charging times. Placing the winding at quadrature resulted in a 4% increase in overall effeciency, but also resulted in a 5% increase in peak current and about a 20% increase in launch package acceleration.

The four-pole, 42-turns per pole CW consists (per pole) of 14 single shorted turns, and a series multi-turn outer winding. The windings are insulated and epoxy vacuum impregnated into machined grooves in a monolithic titanium forging. This hybrid winding scheme was chosen to limit action and radial magnetic loads. Design CW temperature rise after a full salvo is 15 C, while peak inward magnetic pressure is 1,150 psi. The CW conductors are 3/8-in. square compact copper Litz wire with a packing fraction of approximately 60%. Critical CW mechanical design issues centered on differential expansion stresses between the epoxy/litz matrix and the CWSS groove sidewall. This bond must react radial magnetic loads in shear. Because of the thermal mismatch between titanium and epoxy resin, the litz/epoxy matrix, which achieves a neutral state at cure temperature (180 to 250°F), tends to shrink away from the sidewall when cooling, resulting in high residual stresses at room temperature. Plane strain and 3-D finite element modeling and analysis of the axial and end-turn regions of the CW revealed peak shear and tensile bond region stresses of approximately 1.8 and 5.0 ksi, respectively which could be negated by a slight radial preload of the entire structure following potting. It is critically important to ensure that no neat epoxy is exposed to any of the thermal stresses; glass reinforcement takes care of this.

Field Winding

The CPA field coil is comprised of two concentric aluminum cylinders each divided into four quarter sections that have been spirally cut into a sweet roll configuration and are welded together to form a four pole series winding. The two layer design was chosen to minimize manufacturing time by reducing the number of sections to be cut and the number of internal electrical connections to be made. This also positively effects the electrical performance of the winding by increasing the current-carrying capacity of the conductor since its cross-sectional area is increased, i.e., the peak mmf is maintained using a fewer number of turns. This reduces the resistance of the entire winding which reduces the energy dissipated to heat. Since the field winding is the primary loss mechanism in the CPA, gains in this area are desired. Table 3 lists pertinent field coil parameters.

For the field winding, bond strength and insulation integrity issues dominated the design thinking. Therefore, analysis and testing of various surface preparation techniques for the conductor sections prior to epoxy impregnation was required. Previous work at CEM-UT has produced a database of information regarding this subject; therefore, the test plan involved analyzing previously used techniques in the current design configurations. Fundamentally, all exposed surfaces of the winding sections are sandblasted to increase the available bond area, cleaned and de-oxidized in an acid solution, and electro-statically sprayed with a 0.13 mm thick coat of an insulating epoxy paint, in this case, Limitrak®. Primary insulation is provided by a Dow D.E.R. 332 resin system via a vacuum-pressure impregnation process (VPI) in order to minimize void content. The Limitrak® paint eliminates the possibility of re-oxidation of the surfaces and provides redundant insulation. Prior to the VPI process, each coil section will be spread apart to apply a continuous piece of 0.20 mm thick braided E-glass sleeve around each conduc-

Table 3. Field coil parameters

Number of poles	4
Number of turns/pole	64
Resistance	23.4 mΩ
Inductance	2.00 mH
Terminal voltage	3.8 kV
Peak current	25 kA
Current Density	7.54 kA/cm^2
Stored magnetic energy	624 kJ
Packing fraction	87.3 %
Weight	250 kg

tor leg. Connection between the winding sections is achieved using a J-groove weld configuration and the TIG welding process. Care must be taken during welding to avoid charring the previously-applied fiberglass cloth or Limitrak® paint.

Current Collection

Current collection is accomplished via a brush mechanism connecting the primary armature winding of the compulsator to the launcher switch modules. The brush mechanism operates at 3.8 kV and 835 kA peak. High voltage electrical insulation, current distribution, ohmic heating, and large integrated I^2t values presented the greatest design difficulties. Overall, the single most important issue regarding the design of the brushes has been in current sharing for this ultimately defines the duty limits for the brush design.

Series resistance has been carefully added to the brushes in order to force better current sharing. Figure 6 is a plot of the current distribution in the CCEML brushes. This result was obtained by modeling the various brush paths in the discharge circuit. In addition, a transient EMFEA has also been implemented. The purpose of this analysis was to determine current distributions in the slip rings and collector housings, thus ensuring that all forces and heat sources are properly accounted for.

Each terminal of the brush mechanism is made up of twelve rows of seven brushes. The brushes operate at a nominal current density of 3.97 kA/cm^2 and are formed by silver brazing a 0.635 cm x 1.27 cm x 1.91 cm block of Morganite CM1S copper graphite to laminated, highly resistive straps. A resistivity of 1200 μΩ is desired to reduce transient current distribution problems due to inductively preferential current paths through the inner rows of brushes at each terminal. A method used in the past has been to add a series resistor to each brush to achieve this level of resistance. Space constraints on the CCEML compulsator have precluded this method, driving the design towards making the brush straps themselves carry this duty. However, thermal issues result from this decision due to I^2R heating. Detailed analysis has indicted that beryllium copper material be used for the brush straps.

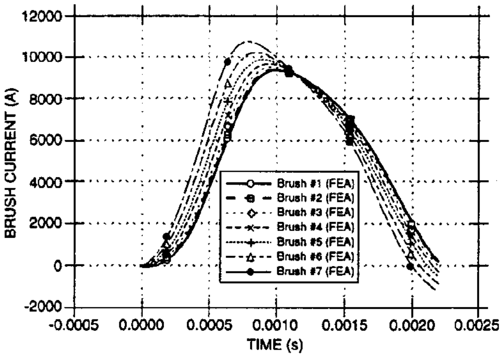


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Figure 6. Brush current distribution plot

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