FIELDABLE EM GUN DESIGN

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Abstract

This paper describes the design of an electromagnetic (EM) gun capable of delivering launch packages at 2.5 km/s. The gun design methodology targets four areas where launcher technology must be advanced: efficiency, energy recovery, design robustness, and managing the interfaces while integrating the design with the "system." System simulations indicate that a 3.2 MA current supplied from a pulse alternator will achieve the design goals. The EM gun design presented features a novel bore cross-section that minimizes bore area while accommodating any round projectile up to 90 mm in diameter. The rail-to-rail spacing is 105 mm. The bore-cross section design is the result of a parameter study that trades EM gun performance against launch package, rail thermal and rail structural risk. The active gun length is 6.0 m and the projected weight including breech, muzzle connections and recoil mechanism is 1,500 kg. (3,300 lb). The structural stiffening mechanism of the gun is based on directional preloading, high modulus sidewall insulators and a lightweight composite overwrap. This same approach was successfully implemented in the Cannon Caliber EM gun. Also, like the Cannon Caliber EM gun, the presented gun design utilizes active liquid cooling. This paper documents EM gun design work performed by UT-CEM, SAIC and General Atomics for a proposal.

Background

The primary objective of this effort is clearly delineated by the US government: improve EM gun characteristics for weaponization. The potential benefits of the EM gun for battlefields of the future are indisputable. Higher velocity means shorter time of flight from gun to target.

Higher impact velocities enhance lethality. Removal of gun propellant from the logistics train will be a large benefit. The key to realizing these benefits is developing EM technology to the point where the system efficiency allows reasonably sized pulse power supplies and a barrel that can launch overwhelmingly lethal projectiles.

UT-CEM, SAIC and General Atomics performed this gun design effort in support writing a proposal. UT-CEM and several other organizations have built and tested large electromagnetic guns with 90 mm bores and lengths from 7 to 10 m. Most large EM guns built to date have been laboratory guns with little consideration for fieldability. One exception to this is UT-CEMs' "Task C 9 MJ gun" built in 1993: a 90 mm bore gun, 7.5 m active length, designed for 3.2 MA peak currents and weighed 3295 kg [1]. This gun design included coolant passages, flexible breech conductors stainless steel laminations to enhance the inductance gradient and a composite overwrap. The gun demonstrated an inductance gradient of 0.49 μH/m.

The EM gun design process begins with an objective payload and muzzle energy being defined. Bore cross-section is optimized for inductance gradient and armature performance and acceleration length is typically defined by the payload's maximum acceleration limitation and power supply characteristics. Most EM gun designers agree that minimizing bore deflection is crucial to prolonging armature performance and maintaining a dimensionally stable and straight bore. Armature performance in turn will affect bore surface degradation and reduce bore life. Bore stiffness may be accomplished by providing a sufficiently rigid structure behind the rails to limit displacement as the EM loads are applied to the rails. Alternatively, mechanically stiff bore components (primarily the sidewall insulators) will also produce a very stiff gun if a preloaded condition is maintained between the rails and insulators such that a gap in not opened up. The stiffening mechanism is comparable to a bolted joint; stiffness is primarily derived from the components being clamped and not the clamping structure itself.

Many railguns have been built that utilized preload to clamp bore components and minimize assembly clearances. In 1986, UT-CEM (Task B 9 MJ gun) built a "hydraulically preloaded" gun designed to maintain a compressive preload state in a stiff ceramic backing structure [2]. Sparta built a similar gun in 1992 [3]. These guns have extremely stiff structures but unfortunately they are also very massive. The UT-CEM's, 10 m "Task B" gun had a peak deflection of 0.3% and weighed 27,300 kg (30 T); obviously the gun was designed strictly as a laboratory gun. Both the Sparta gun and the UT-CEM gun utilized hydraulic preloading schemes that applied the preload over 360 degrees of the bore package. A variant of this approach is a directionally hydraulic preloading. General Atomics built several directionally preloaded hydraulic EM guns and ultimately patented a directional preloading concept in 1990 [4]. A similar UK patent was filed in 1986 by Martin [5]. This same preloading scheme was adopted for the Cannon Caliber barrel built in 1993 [6]. A hydraulic preload system for gun preload adds an auxiliary burden. It may provide a gun performance diagnostic and permit adjustments to gun preload and straightness as operating conditions change. Replacing hydraulic mediums with filled epoxies and low melting temperature metals is also an option that reduce active auxiliary requirements. Another directional preloading scheme eliminates the need for hydraulics uses jacks to separate the rails radially outward away from each other and wedges a pair of oversized, insulating members to retain the preload [7]. The Institute for Advanced Physics (IAP) has designed and built prototype guns that utilize this preloading mechanism [8]. Difficulties with this approach include complicated expansion and assembly tooling and high manufacturing tolerances if tapers are used.

EM Gun Design

The launcher bore cross-section is a novel shape that minimizes bore area while accommodating any round projectile up to 90 mm in diameter (Figs. 1 and 2) The rail-to-rail spacing is 105 mm. The novel geometry and several other feature have been included to allow the armature and sabot designers the flexibility and freedom for optimization. This bore will accommodate long rod, chemical and indirect fire rounds. First level trades performed resulted in a maximized inductance gradient without imposing added burdens on the launch package design. The muzzle includes a shunt designed to permit efficient energy recovery, reduce EM signature, and minimize tip-off problems that might hinder accuracy. The active gun length is 6.0 m and the projected weight including breech, muzzle connections and recoil mechanism is 1,500 kg (3,330 lb).

Minimizing bore growth is essential to maintaining a nontransitioning armature and a gun structure with a stable bore dimension. The structural stiffening mechanism of the gun is based on directional preloading, high modulus sidewall insulators and lightweight composite overwrap. This approach was successfully implemented in the Cannon Caliber EM gun program and resulted in one of the most fieldable EM guns ever built and tested (Fig. 3). A similar preload scheme has been adopted for this design.

The baseline gun design incorporates chromium copper rails with an explosively bonded, hardened, steel bore-liner and sidewalls composed of high modulus alumina ceramic (Coors AD-96). The rails and sidewall assembly are overwrapped with an epoxy impregnated mica insulation which serves as electrical insulation between the rails and the surrounding structural components. Pre-compression of the rail and sidewall assembly is accomplished by a pair of hydraulically preloaded metallic bladders or “flat jacks.” A very high gun stiffness (<0.2% bore deflection at peak load; Task B gun 0.3%, Task C gun 1.0%) is achieved because the pre-compressed state of the bore components is maintained at peak gun current. The gun’s stiffness is primarily attributed to the very high modulus, 303 Gpa (44 Msi), ceramic sidewall insulators. The gun preload and EM loading is reacted by the graphite composite overwrap. Fig. 4 illustrates the preloading of EM gun bore components and the effect on bore stiffness. The composite overwrap also provides longitudinal barrel stiffness by the presence of axial fibers. Outboard of the graphite composite overwrap is a replaceable thin housing of armortex bullet resistant fiberglass to protect the gun tube from small arms fire and exploding fragments.

Initial calculations indicate that a 138 MPa (20 ksi) flatjack preload will be sufficient to maintain a compressive stress state in the gun's bore components at the peak gun current of 3.29 MA. This peak EM loading results in a force per unit gun length of 15 MN/m (83.2 kip/in.) and the flatjacks provide 22.0 MN/m (126 kips/in.). The load transmitted to the composite overwrap will be approximately 30% above the initial preload or 18.9 MN/m (108 kips/in.). The average stress in the composite overwrap at peak gun current is therefore only 296 MPa (43 ksi). Graphite composite materials used by other UT-CEM programs have demonstrated ultimate strengths in excess of 2.4 GPa (350 ksi) with very good resistance to viscoelasitic behavior at elevated temperatures. Assuming a stress gradient of two, a factor of safety of 2.0 may be accomplished with only 60% of the area. The remaining composite overwrap cross section may be dedicated to longitudinal fibers to maximize barrel stiffness. Additional barrel stiffness will be gained by utilizing sections of the composite spacer (outboard of flatjacks) for longitudinal fibers.

Breech Connection

A breech design was adopted for the proposed gun that is based on a design that has been successfully implemented on several UT-CEM railguns. The breech design as shown in Fig. 5 consists of two parallel aluminum plates normal to the axis of the gun and separated by electrical insulator plates. The upper conductor is terminated in the first plate (nearest the gun) and the joint preload is accomplished by a pair of mechanical jacks (tapered wedge jacks) located on the sides of the rail. The inside geometry of this plate nearest the gun allows the lower conductor to pass through the plate and be terminated in a similarly to the upper conductor. The outside dimensions of the two breech conductors are sized to replicate the structural stiffness of the active length of the gun. The recoil force is managed in the design and support of these plates. The design is simple, low inductance and adds very little to the overall gun length. The design also permits easy access to the bore for projectile loading and bore maintenance.

Muzzle Switch Connection

A muzzle switch attachment concept is shown in Fig. 6. A pair of symmetric, longitudinal slots are milled through the sides of the composite overwrap. The rail thickness is locally reduced to accept a conductor that passes through both sides of the structure. The flatjack provides clamping pressure. The overwrap thickness is increased in the region around the penetrations and insulating grommets block line-of-sight between the conductor and the graphite composite overwrap. This connection scheme was used on the Cannon Cal EM gun. The resulting symmetrically protruding conductors may be configured for a passive muzzle shunt or (as in the case of Cannon Cal) a low inductance, SCR muzzle switch.

Rails

The baseline rail material is chromium copper (UNS C18200) with an explosively bonded, hardened steel bore-liner. Chromium copper as the rail material represents a very good compromise between mechanical and electrical properties. In forging form, chromium copper has demonstrated 0.2% offset yield strengths of 310 MPa (45 ksi) and an electrical conductivity of 85% IACS. The material is dimensionally stable (does not distort when machined like dispersion strengthened alloys like GlidCop Al-15) and relatively low cost. The rails are cooled by pairs of 8 mm (5/16 in.) diameter coolant passages that run the full length of the gun. Return coolant passages are imbedded in the composite structures behind the flatjacks. The rails extend the full width of the inside dimension of the composite overwrap. However, the active region of the rails or the region the carries current is only 75 mm wide by 25 mm thick. This is accomplished by slitting the rails normal to the bore centerline along the full length of the gun with 3.2 mm (0.12 in.) wide slots and 6.4 mm (0.25 in.) spacing. Rail slitting permits the current carrying portion of the rail to be optimized for inductance gradient and allows the rails to be utilized for structural and thermal management. Rail slitting was demonstrated as an effective means to maximize launcher inductance gradient on several past UT-CEM programs. Extensive test programs were conducted to demonstrate that the slotted section of the rails has a minimal effect on the inductance gradient [6].

Sidewall Insulators

Very high modulus sidewalls are required to achieve an EM gun bore stiffness comparable to conventional tank guns. Coors alumina ceramic AD-96 exhibits excellent mechanical and electrical properties. Coors AD-96 naturally prefers a compressive stress state, is creep resistant, and a very good insulator at very high temperatures. The Cannon Caliber EM gun utilized 2.25 m (88 in.) long, Coors AD-96, sidewall insulators. The Cannon Caliber EM gun sidewalls exhibited good wear characteristics and very good toughness when exposed to muzzle currents in excess of 375 kA. Manufacturability issues with the long ceramic sidewall sections may necessitate multiple joined sections.

Flatjacks (preload mechanisms)

After an extensive trade study, the Cannon Caliber EM gun program selected annealed Inconel 718 as the flatjack material. Inconel 718 in the annealed condition has high strength and ductility and is readily welded which is necessary for manifolding and making high pressure connections. As previously stated, the minimum flatjack pressure necessary to maintain a compressive stress state in the gun is estimated to be 138 MPa (20 ksi). This was also the operating pressure of the Cannon Caliber gun. Cannon Caliber gun mock-ups were pressurized in excess of 207 MPa (30 ksi) during the program’s component development phase. Hydraulic pressurization may be performed with a variety of mediums. Glycerin allows the flatjack pressure to be monitored and adjusted as the gun is exposed to different operating environments. This would be a useful pressurization medium for gun mock-ups and possibly the sub-scale gun so adjustments to gun preload may performed and gun operational effects may be characterized. The use of epoxy as the pressurizing medium eliminates the need for a high pressure connection to the flatjacks; an attractive feature for a fieldable gun. However, epoxy cure shrinkage, creep and dissimilar coefficients of thermal expansion of the gun components must be considered. The solution for the 105 mm fieldable gun is to design in enough margin so the flatjacks can be pressurized to account for epoxy shrinkage, creep and thermal effects over all operating conditions.

Composite Overwrap

B-stage tow preg materials have been used extensively at UT-CEM through several generations of compulsators and high energy density flywheel development activities. UT-CEM also has accumulated an extensive material property database on a variety of state-of-the-art high modulus graphite composite fibers and resin systems. The proposed EM gun composite tube design requires moderate strength and modulus properties in the hoop direction and high modulus and possibly nonconductive properties in the longitudinal direction. Hexcel IM7/8552-1 has a demonstrated hoop strain to failure of 1.3% and has good resistance to creep at temperatures up to 250°F. Candidate materials for the composite fibers in the longitudinal direction include fiberglass (if nonconducting is a requirement) and high modulus graphite. Graphite offers a factor of three increase in modulus which may be necessary to meet weight and barrel stiffness requirements.

Rail Ground Plane Insulation

A good candidate for the rail ground plane insulation is a mica B-stage tape such as Cogebi, Inc. 631-12-38. A 1.3 mm (0.05 in.) thick layer may be built up around the rail and sidewall insulator assembly and cured to form a very tough, ground plane insulation system. This material has a compressive strength of 296 MPa (43 ksi) at room temperature. The rails and sidewall assembly are overwrapped with the epoxy impregnated mica insulation which serves as electrical insulation between the rails and the surrounding structural components.

Thermal Management

The predicted heating in the full-scale launcher is 2.41 MJ per shot, equally divided between the two rails. The goal of the launcher cooling system design was to assure that all of the ohmic heat deposited in the rails could be removed within 30 s (two shot per minute steady-state firing rate). Two barrel cooling concepts, circulating liquid and air exhausting through the muzzle were considered. It was found that the 80 kW steady-state heat removal rate could be accomplished most effectively with liquid cooling. A mixture of 60% water and 40% ethylene glycol was assumed for the cooling analysis.

The gun is actively cooled with ethylene glycol flowing through pairs of cooling passages that run the full length of the rails. Coolant enters at the breech via insulated, flexible hoses and returns through coolant return lines imbedded in the composite spacers outboard of the flat jacks. This minimizes external auxiliary connections and locates them at the breech end of the gun.

Risk Reduction

Risk reduction activities for the proposed gun included a 1/2 scale launcher for validation of performance characteristics, structural and thermal management, manufacturing processes and fieldability issues (life, robustness and mobility loads). Table 1 gives performance and physical parameters of the full and subscale EM guns

Conclusions

This paper describes the design of an 6 m long, EM launcher with an overall mass of approximately 1500 kg. The design leverages off of demonstrated EM gun materials and construction techniques.

Acknowledgments

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References

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Table 1. Performance and physical parameter of the full and sub-scale EM guns.

PARAMETER	**FULL-SCALE EM GUN**	**SUBSCALE EM GUN***
Bore Height	105 mm	52.5 mm
Bore Width (@ midplane)	90 mm	45 mm
Rail Width (active)	75 mm	37.5 mm
Rail Height (active)	25 mm	15 mm
Barrel Overall Height	38 cm	19 cm
Barrel Overall Width	28 cm	14 cm
Gun Length	6 m	3 m
Launcher L’	0.595 μH/m	0.617 μH/m
Peak Current	3.29 MA	1.61 MA
Projectile Velocity	2500 m/s	2500 m/s
Barrel Weight	1493 kg	150 kg
Breech Weight	42 kg	6 kg
Muzzle Attachment Weight	31 kg	4 kg
Auxiliary Hardware Weight	220 kg	28 kg
Total Gun Weight	1493 kg	188 kg
Peak Repulsion Load	83.2 kips/in.	40.0 kips/in.

*Subscale dimensions and weights based on scaling from full-scale design

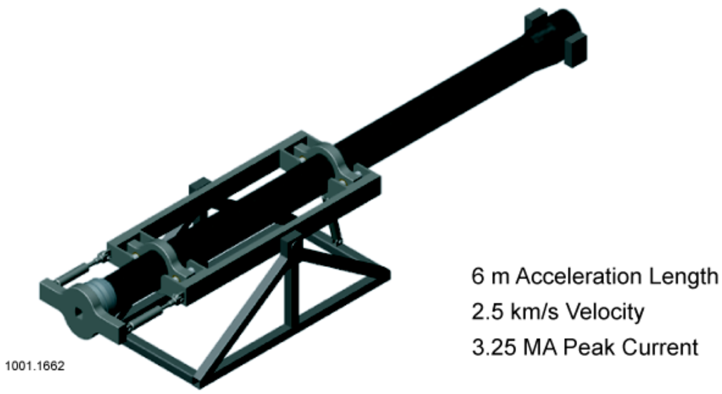

Figure 1. Full-scale 105 mm EM Gun

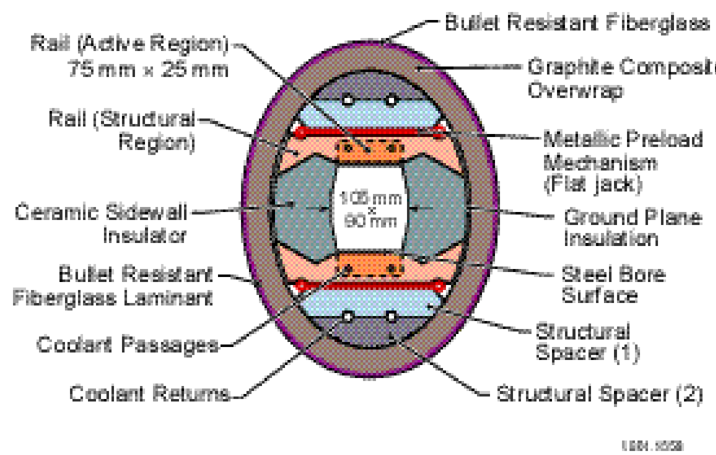

Figure 2. EM Gun cross-section

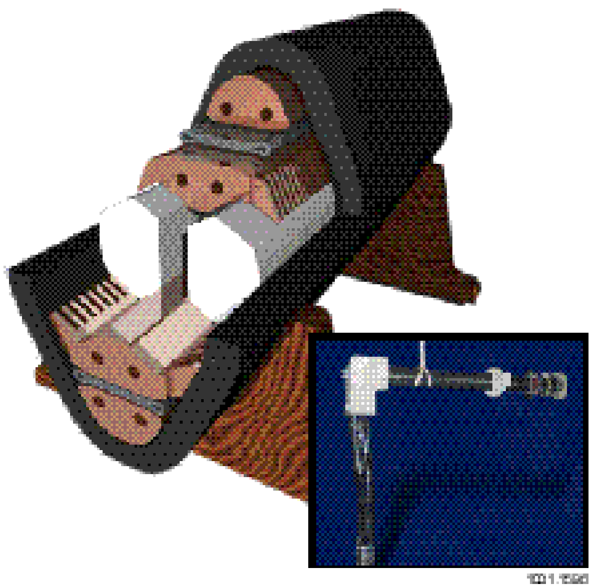

Figure 3. Cannon Caliber Gun

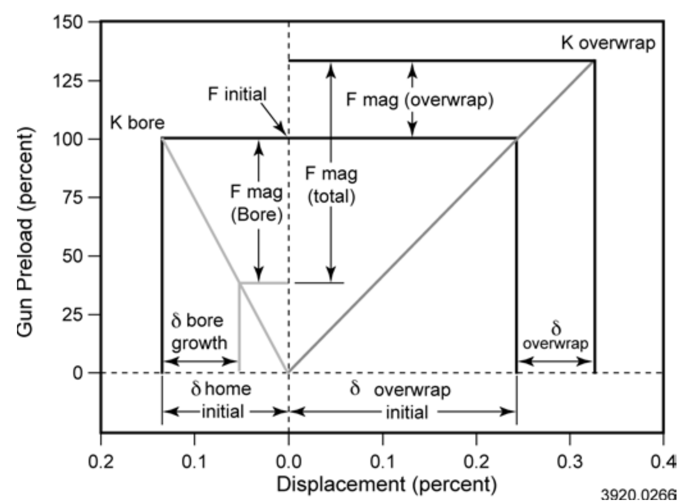

Figure 4. Normalized force vs. bore displacement curve for preloaded EM guns

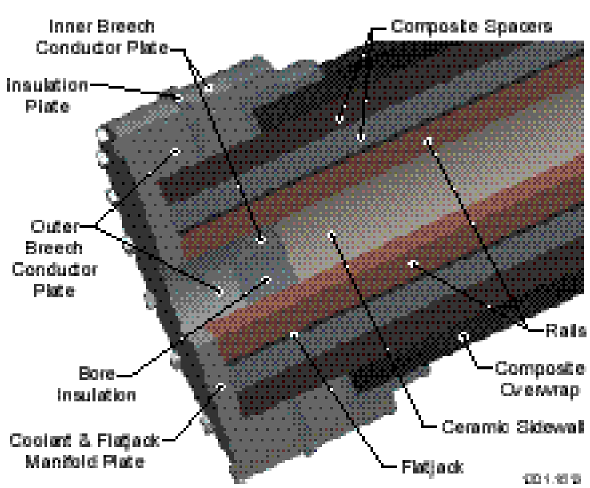

Figure 5. Breech design

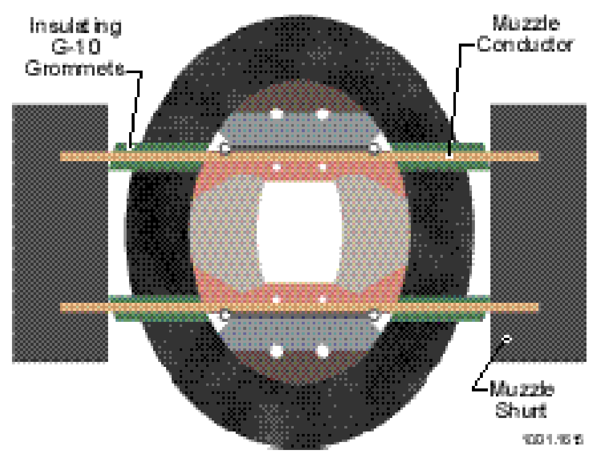

Figure 6. Muzzle switch attachment concept