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APPLICATION OF SUPERCONDUCTING TECHNOLOGY TO EARTH-TO-ORBIT ELECTROMAGNETIC LAUNCH SYSTEMS

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APPLICATION OF SUPERCONDUCTING TECHNOLOGY TO EARTH-TO-ORBIT ELECTROMAGNETIC LAUNCH SYSTEMS

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ABSTRACT

Benefits may occur by incorporating superconductors, both existing and those currently under development, in one or more parts of a large-scale electromagnetic launch (EML) system that is capable of delivering payloads from the surface of the Earth to space. The use of superconductors for many of the EML components results in lower system losses; consequently, reductions in the size and number of energy storage devices are possible. Applied high-temperature superconductivity may eventually enable novel design concepts for energy distribution and switching. All of these technical improvements have the potential to reduce system complexity and lower payload launch costs.

INTRODUCTION

Several mission studies have examined Earth-to-space EML of nonfragile cargo [1-4]. The use of either rail or coaxial accelerator systems appears technically feasible for these missions; however, the large capital costs of contemporary designs indicate that such systems will not be economically attractive until some time in the future when high launch rates are needed, i.e., on the order of 6000 kg of payload per day.

The projectile masses, accelerator lengths, and energy requirements of existing EML facilities are many orders of magnitude smaller than those required for large-payload space launch systems. Given these large differences, simple scale-up of conventional designs is not likely to result in optimized designs. Rather, novel designs may be necessary to make EML technology superior to competing technologies at this scale.

Hull and Carney [5] discussed the incorporation of superconducting technology in the design of Earth-to-orbit (ETO) EML systems in ways that have the potential to significantly reduce the capital costs. This paper summarizes the results of Ref. 5. We consider both rail accelerator and coaxial EML technologies and compare designs that use nonsuperconductors, conventional superconductors, and high-temperature superconductors (HTSs) that are currently under development. HTS refers to the class of ceramic superconductors (e.g., yttrium-barium-copper-oxide, bismuth-strontium-calcium-copper-oxide, and thallium-barium-calcium-copper-oxide) that have been shown to definitely have superconducting properties at temperatures above the boiling point of nitrogen (77 K).

The mission reference concept chosen [2] for this analysis is the launch of 6000-kg (rail) or 3000-kg (coaxial) projectiles to a velocity of 7

km/s at an acceleration of 1225 g through a 2 km-long launcher with a bore of about 1 m, elevated 20 degrees from the surface of the Earth.

DESIGN OPTIONS

The major obstacle to an ETO EML is the large capital expenditure, and designs that significantly reduce this cost are of most value. Although the launch energy itself is very inexpensive (<$1/kg to LEO), the cost of storing it so it is rapidly accessible is expensive. A major challenge to EML development is therefore power conditioning, or more specifically, power compression. With this in mind, this section examines the impact of applied superconductivity on the various EML subsystems of both rail accelerator and coaxial magnetic accelerator systems, evaluated with regard to the promise it has in reducing either system complexity or cost.

Energy Storage

A limitation of the railgun is that it is basically a single-turn motor and therefore requires a very high current at relatively low voltage. Typical rail accelerator operation involves currents on the order of 10^5 to 10^6 (or higher) A. Homopolar generators (HPGs) are an attractive power source because they are very efficient at high currents; however, they do not provide sufficient voltage output (back emf) to drive a rail accelerator. Consequently, HPGs are generally matched to a low-impedance inductor to provide the required current and voltage.

The Battelle studies [1,2] envisioned cryogenically cooled [using liquid nitrogen (LN_2)] inductors matched to the HPGs for both the rail

accelerator and coaxial EML concepts. The rail accelerator system, operating at high current at relatively low voltage, requires many HPGs with individual LN_2 inductors; the coaxial magnetic launcher, operating at high voltage at relatively low current, would require a single LN_2 coil. Use of superconducting inductors between the HPGs and the rails offers the opportunity to increase the efficiency of energy transfer in the switching circuits and thereby significantly reduce the number of HPG/inductors required.

The primary function of the HPG is to bring the inductor up to voltage. For nonsuperconducting inductors this "charging" must be relatively fast to minimize resistive-heating losses in the coils. However, for superconducting coils the charging can be as long as the period between lauches. The inductor charging could then be readily accomplished by means of a Graetz bridge circuit [6], similar to that envisioned for superconducting magnetic energy storage coils for utility load leveling or pulsed fusion magnets. The input to the Graetz bridge would lead directly to the power transmission lines; the output would lead to the inductors. Each HPG would be replaced by three thyristor (or possibly superconducting - see below) switching units. For a charging time of 1 hr, each Graetz bridge unit would need a power rating of 16 kW to charge a 56 MJ coil.

With inductor energy storage, advantage is gained if the energy can be stored in one large inductor. For example, a thin coil of radius R and fixed ampere turns contains stored magnetic energy that is approximately proportional to $R\ln(R)$. The cost of the coil is roughly proportional to R, and therefore the cost of stored energy varies as $1/\ln(R)$.

Rails and Components of Rail Accelerator Systems

One of the biggest drawbacks of a simple rail accelerator system is that it is an inherently inefficient device since only a fraction of the energy supplied to the accelerator is converted into the kinetic energy of the projectile. This inefficiency is due to the high resistive-heating losses in the rails and armature and also to the energy which remains stored in the magnetic field between the rails. The resistive losses of excessively long accelerators can be prohibitive.

An alternative option would use actively cooled superconducting rails to carry the large currents, with a copper (or another highly normal conductor, such as amzirc) veneer to transfer the current to the armature. The advantage of this option, which would require HTSs to be viable, is that the absence of large I^2R losses enables the launcher to be powered by a single large inductor coil connected to the rails at the breech of the accelerator. Such a design would benefit from the scaling laws discussed in the previous section.

Resistive losses would still occur in the armature, as in DES designs. There would be some Joule heating in the copper as the projectile passes, until the current could diffuse into the superconductor. Using the ESRL concept developed by Miller, et al. [2] as the basis for comparison, this scheme greatly reduces the number of HPG/inductor units required in a conventional segmented rail accelerator.

If the resistance heating is decreased by a factor of ten and all of the rail heat is transferred to boiling LN_2 (latent heat 161 MJ/m^3), then approximately 50 m^3 of LN_2 is required (about $10K) per launch. If liquid helium (latent heat 2.62 MJ/m^3) is used instead, about 3000 m^3 is required

(about $6M) per launch. Based on cooling costs alone, it appears that this design option will require that HTSs be feasible.

Of equal concern as resistive heating is, that in a breech-powered circuit, an amount of energy equivalent to the projectile kinetic energy is stored in the magnetic field of the rail inductance. This energy must be dissipated or recovered after the projectile leaves the muzzle. With a DES system only a small amount of magnetic energy is in the rail system, and these losses are then insignificant.

Another reason for a DES design is that the railgun is usually operated at the maximum acceleration that either the launcher or projectile can tolerate. The accelerating force is limited by the need to hold the rails together against magnetic bursting forces, which are the equivalent of the gas pressure in a gun barrel. It is then desirable to have a constant current in the rails to keep the acceleration at its maximum. If the current falls with increasing projectile position, then the launcher must be made longer to compensate for the reduced acceleration. To minimize this effect in a single coil system, the energy stored in the large coil must be significantly larger than the energy delivered to the projectile.

Superconducting Augmentation of a Railgun

A third major option for railguns involves the use of a superconducting dipole magnet to augment the force on the projectile of an otherwise conventional railgun system, allowing the use of smaller currents in the rails and possibly alleviating some of the switching constraints and component stresses. A dc dipole magnet would provide a strong magnetic field along the length of the rails. Except for the ends, the dipole would

consist of a set of long superconducting cables of a relatively simple fabrication.

One major technical issue with this type of system is that the size and weight of the superconducting magnet makes the augmentation impractical. Use of HTSs could potentially reduce the requirements and increase the current capacity of the magnet, make the massive cryogenic portion of the magnet unnecessary, and provide significantly higher magnetic fields.

Projectile Coils for Coaxial Magnetic Accelerator System

Coaxial EMLs can be classified by the way synchronization is achieved and by how the projectile coil current is obtained. For low velocity devices the projectile current can be obtained by commutator brushes, and this technique can be used to accelerate very large masses. The barrel coils can take the form of a single helically-wound coil. However, for velocities higher than about 1 km/s, commutation is no longer feasible [7].

Two alternatives are possible to brush-fed excitation. One is to short-circuit the projectile coils and induce a current in them. The second is to use superconducting projectile coils energized with a persistent current before the bucket is launched. In either case, the barrel coils usually take the form of discrete loops, each separately pulsed. An advantage of the noncontacting nature of the projectile coils in these approaches is that there is no wear on the system, an advantage over the rail accelerator as well as the brush-fed method.

Based on an analysis of pinning forces [8], superconductors can easily withstand the forces generated in EML devices. Of greater concern is the heat generated in the superconductors. In a coaxial EML, the bucket coils

experience a constant magnetic field to first order, i.e., they see essentially a dc magnetic field. An ac component to this field occurs because of the discreteness of the drive coils and because the bucket does not travel on its equilibrium trajectory, but rather experiences small oscillations about it. An ac field component may also appear because of imperfect timing in switching circuits. The ac field induces eddy currents in the projectile coil. While these currents are much smaller than those that must be induced in a nonsuperconducting coil, they are nevertheless large enough to drive a conventional superconducting coil nonsuperconducting. If this occurs, the projectile coil current soon disappears and acceleration stops.

Wipf [8] estimates that the ac loss of a superconductor for a 0.1 T peak field is 1 to 10 $\mu J/cm^2$ of surface per cycle. In the reference design [2], each projectile coil carries a current of 250 kA along a circumference of about 70 cm. Drive coils are spaced every 16 cm. If we assume a superconducting current density of 10^5 A/cm^2, then each projectile coil has a volume of 245 cm^3 and a surface area of 450 cm^2. Assuming that 10 $\mu J/cm^2$ is deposited for every drive coil, the total energy deposited in the projectile coils is about 200 mJ/cm^3.

Conventional superconductors can only tolerate 10 (for NbTi) to 100 (for Nb_3Sn) mJ/cm^3 of heat addition before losing the superconducting state, and in this example the nonuniform field experienced by an accelerating projectile would add more than this amount of energy to the projectile coils. By comparison, the new HTS materials may absorb about 100 J/cm^3 before losing superconductivity. This 1000- to 10,000-fold increase definitely enhances the prospects of superconducting projectile coils.

Drive Coils for Coaxial Magnetic Accelerator System

Superconductivity can be used in the drive coils to reduce the coil size and increase the mutual inductance between drive and projectile coils. Because the HTS materials will tolerate, in theory, much higher magnetic fields than conventional superconductors, they will allow a smaller clearance gap between drive and projectile coils and therefore higher accelerations, at least from the standpoint of magnetics criteria.

Energy Switching

Energy switching can be a large cost component of either a rail accelerator or coaxial EML system. For both rail accelerators and coaxial launchers, switches must be able to handle currents on the order of 1 MA, several tens of kV, and switching times of microseconds to milliseconds.

For coaxial magnetic launchers, switching and control is even more critical than it is for rail accelerators. The drive coils in a coaxial EML can be made with multiple turns, to make them operate at lower currents and higher voltages than rail accelerators. At the same time, the coils are only closely coupled when they are close together, say within one coil diameter. This requires that the power pulse in the drive coil be closely synchronized with the passing of the projectile. The short transit time of the projectile through the active region of a drive coil reduces the time for signal propagation and switch turn-on. Because of the time available for pulsing the drive coil is short, a large dI/dt is necessary, and higher speeds result in higher voltage requirements. At 7 km/s, the pulse voltages of the drive current are about 100 kV [2]. The switching issue is not one

of technical feasibility (large accelerator magnets are pulsed with comparable power and shorter times), but rather one of economics.

The availability of HTSs may open the way for low-cost, large-current, high-voltage opening switches with fast switching times. Several designs that use conventional superconductors have already been investigated [9]. The HTSs have several advantages over low-temperature superconductors (LTS) in switching applications. The volume V of superconductor needed for a switch is given by [9]

$$V = P_{max}/(\rho_N J_c^2) \ , \tag{1}$$

where P_{max} is the peak power to be transferred, ρ_N is the normal state electrical resistivity, and J_c is the critical current density. The normal-state resistivity of the ceramic HTSs is much higher than that of their LTS counterparts. Assuming equal J_c, the volume of superconductor required for an HTS switch should be small. A second advantage is that the auxiliary cooling requirements of an HTS are much smaller than those of an LTS.

In the switch, the HTS would be combined with a structural material of low conductivity. It would be connected to a nonsuperconducting shunt of high conductivity, such as a pair of rails or a drive coil. When the switch is in the closed position, the HTS is in the superconducting state. When the switch is to be opened, an external magnetic field, laser-driven heat pulse, or current pulse is imposed to drive the HTS normal and rapidly transfer the current to the shunt circuit. A preferred geometry for such a switch is a thin film [9]. Thin films may be the first fabricated forms for the new HTS material. Such switches may allow direct coupling of EML devices to superconducting inductors.

Transmission-Line Storage

If superconductivity enables a low-loss system, then it may be practical to construct the coaxial coils (or rail accelerator inductors) in such a way that the system forms a transmission line, which stores within it all the energy that is necessary for launch. The energy would travel down the transmission line at a speed synchronized with a projectile launch and be reflected at each end. The synchrotron oscillation principle could be used to keep the projectile in phase with the traveling wave. The disadvantage of such a system is that the drive coils would be regularly pulsed, which would add to their fatigue wear. In addition, the scaling of the launcher may make such a system unfeasible. Nevertheless, the potential for minimal-switching, traveling-wave accelerator concepts needs to be explored further [10].

CHALLENGES

Clearly, any significant development in technology that minimizes the complexity of the design requirements of the ETO EML system or its components, maximizes the launcher system efficiency, or in some other way reduces the large up-front capital investment is an "enabling" technology. As we have seen in the previous section, superconductivity, and especially the HTS, has the potential to significantly reduce capital costs.

The difficulty for future HTS applications arises from the present fabrication techniques, which produce wires and tapes in a polycrystalline form. Critical transport currents in such structures have so far been low

because of randomly oriented crystal alignment and poor conduction at crystal grain boundaries. In addition to the poor geometric match inherent in polycrystalline structures, there appears to be an intrinsic insulator at the boundary of each individual crystal.

While up to 200 T has been estimated for the upper critical field in HTS materials, the ability to achieve fields over 10-20 T will undoubtably be limited in practice by the strain induced by stresses connected with containment of the high magnetic fields. For pulsed fields, the limitation is even more severe. It is customary to have maximum conductor tensile strains of several tenths of a percent for NbTi, a very ductile material, and it is unlikely that such strains can be supported by the brittle ceramic HTSs, even with the coils designed to always remain in compression. Thus, unless a breakthrough occurs in the mechanical properties of HTSs, significant quantities of high-modulus support structure, closely coupled to the HTSs, will be needed to limit the strain on any magnet coils.

CONCLUDING REMARKS

This paper has examined the incorporation of superconducting technology in the design of Earth-to-orbit electromagnetic launch systems. Both rail accelerator and coaxial magnetic accelerator devices were considered, using the reference concepts developed under previous NASA studies as the basis for comparison. The use of both conventional and advanced, high-temperature supeconductivity can potentially improve EML technology at the subsystem and component levels. Some of the major technical benefits in the use of superconductivity may be realized in the following areas: EML components (rails, coils, power lines, etc.); energy storage; energy switching;

superconductive magnetic augmentation (rail accelerator); projectile and drive coils (coaxial magnetic accelerator); and transmission line storage (coaxial design).

One primary application of superconductivity would be to improve the energy storage and distribution system required for a large-scale EML. Reductions in the size and number of energy storage devices are possible with applied superconductivity. The use of superconductors for many of the other EML components would result in lower system resistive losses and may even enable new design concepts for energy distribution and switching. All of these technical improvements have the potential to reduce system complexity and lower payload launch costs.

While the field of high-temperature superconductivity is developing very fast, the final properties that may become available cannot be known at this time. Significant improvement in the strength properties of bulk HTS materials is required before HTS can be considered a viable option for EML technology areas.

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