THEORETICAL ANALYSIS OF A COLLAPSING FIELD ACCELERATOR

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Theoretical Analysis of a Collapsing Field Accelerator

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ABSTRACT—This paper presents a theoretical discussion of a collapsing field accelerator currently under study at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). This accelerator has several novel features, including completely passive, zero-current off-switching of stator coils and quite high efficiency and average-to-peak acceleration. The device serves as its own intermediate energy storage system, and can be powered directly by a homopolar generator.

INTRODUCTION

CEM-UT is currently developing a new coaxial accelerator which has several novel features, including completely passive, zero-current off-switching of stator coils and quite high efficiency and average-to-peak acceleration. The device serves as its own power conditioning system, and can be powered by a homopolar generator.

This paper presents a detailed theoretical analysis of the accelerator, along with simulation results that show its impressive performance. The final section addresses power supply issues, illustrating in particular the impact of power supply selection on overall system efficiency.

THEORETICAL ANALYSIS

This section conducts a detailed theoretical analysis of the accelerator under development at CEM-UT. Fig. 1 provides a general overview of the system, which operates in the following manner:

1. Switch 1 is closed, and current begins to flow into coil S (called the starter coil). The starter coil inductance is chosen so that the current rise time is much greater than the time constant of the armature (coil A). As a result, magnetic flux diffuses slowly into the armature without inducing a large transient armature current.

2. As the flux linking the armature nears the required level, the SCR's are gated, and current begins to flow into all of the barrel coils (coils $B_1..B_n$). The inductance of these coils is chosen to promote a rapid rise of barrel coil current to the required level.
3. When the armature flux linkages and barrel coil currents reach the required level, switch 1 is opened and the starter coil current is rapidly reduced to zero. The resulting emf induced in the armature produces a large, persistent current. The polarity of this current is identical to that of the barrel coil currents; a magnetic force is produced which draws the armature into the barrel.
4. As the armature approaches a barrel coil, there is a tendency for the current in both coils to fall as they begin to share mutual flux linkages. If the current levels are chosen properly, the barrel coil current will be driven through zero just as the armature reaches the centered position. This causes the SCR in the barrel coil circuit to switch off, preventing the barrel coil current from reappearing as the armature moves away.
5. This process repeats itself for each barrel coil. The armature experiences a force drawing it into each stage, and the speed voltage created in the barrel coil by the armature's approach switches the barrel coil off in a passive, self-timed manner.

This section addresses the operation of the launcher itself, after all coils have been brought to the appropriate current levels. Power supply issues are dealt with in the final section of the paper. The operation of a lossless, single-stage (one armature coil and one barrel coil) will be considered initially. Multistage systems with resistive losses will be considered later.

A Flux-Linkage Based Analysis

Fig. 2 illustrates an idealized, single-stage system. Both coils are assumed to be lossless and experience no applied voltage during the launch proper; Faraday's Law states that

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Fig. 1. General overview of accelerator system

the magnetic flux linkages of both coils will remain constant. These flux linkages are related to the coil currents by the following equation:

$$\begin{bmatrix} L_s & M \\ M & L_a \end{bmatrix} \begin{bmatrix} I_s \\ I_a \end{bmatrix} = \begin{bmatrix} \lambda_s \\ \lambda_a \end{bmatrix} \quad (1)$$

The barrel coil and armature self-inductances, L_s and L_a , are constant, but the mutual inductance M is a function of armature position. The condition that the barrel coil current vanish when the armature reaches the centered position can be expressed in the following manner:

$$\begin{bmatrix} L_s & M_0 \\ M_0 & L_a \end{bmatrix} \begin{bmatrix} 0 \\ I_a \end{bmatrix} = \begin{bmatrix} \lambda_s \\ \lambda_a \end{bmatrix} \quad (2)$$

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Fig. 2. Single-stage, lossless accelerator

where M_0 denotes the mutual inductance when the armature is centered. Equation (2) can readily be solved for a relationship between the flux linkages; the result is

$$\frac{\lambda_s}{\lambda_a} = \frac{M_0}{L_a} \quad (3)$$

Equation (3) assumes a more interesting form upon introduction of the coupling coefficient k , which defined by the following equation:

$$k = \frac{M}{\sqrt{L_s L_a}} \quad (4)$$

Substitution of (4) into (3) produces

$$\frac{\lambda_s}{\sqrt{L_s}} = k_0 \frac{\lambda_a}{\sqrt{L_a}} \quad (5)$$

or

$$\frac{\lambda_s^2}{2L_s} = k_0^2 \frac{\lambda_a^2}{2L_a} \quad (6)$$

Equation (6) states that the barrel coil current will vanish when the armature is centered if the magnetic energy stored in the stator coil is equal to the energy stored in the armature times the square of the peak coupling coefficient. Because the coupling coefficient is always less than unity, the armature must store more energy than the barrel coil.

Once the barrel coil current reaches zero, the SCR turns off and the barrel coil becomes an open circuit incapable of carrying current. No further magnetic interaction between the two coils occurs. Equation (2) shows that the armature current at this time is equal to its initial value; the magnetic energy stored in the armature is unchanged. However, magnetic energy is no longer stored in the barrel coil. Because this idealized system contains no loss mechanisms, conservation of energy requires that this energy be manifested as armature kinetic energy. This illustrates the first novel feature of this system: neglecting resistive losses, all magnetic energy initially stored in the barrel is converted to kinetic energy. The efficiency of the single stage system can now be defined as the final kinetic energy divided by the total input energy:

$$\eta = \frac{\frac{\lambda_s^2}{2L_s}}{\frac{\lambda_s^2}{2L_s} + \frac{\lambda_a^2}{2L_a}} \quad (7)$$

Substitution of (6) into (7) and simplification produce the following simple expression for efficiency:

$$\eta = \frac{k_0^2}{1 + k_0^2} \quad (8)$$

Multistage Systems

Equation (8) seems to indicate that for reasonable values of k_0 (e.g., 0.8), system efficiencies will be somewhat low (e.g., 39%). This occurs because more energy must be stored in the armature than the barrel coil, and this energy is not converted to kinetic energy. However, this limitation does not exist in multistage systems. Note that the energy initially stored in the armature remains in the armature after the operation of a stage is complete, and can be reused in subsequent stages. Equation (8) can be modified to reflect the total accelerator efficiency of an N-stage system:

$$\eta = \frac{Nk_0^2}{1 + Nk_0^2} \quad (9)$$

Equation (9) indicates that the efficiency can approach unity as closely as one desires as the number of stages is increased.

Note that this analysis neglects coupling between stages. In systems with significant coupling between adjacent barrel coils the efficiency fails to reach the value predicted by (9). Space limitations prohibit presentation of the necessary algebra, but it can be shown that the total accelerator efficiency is related to accelerator's length-to-bore ratio; the higher the ratio the higher the efficiency.

SIMULATION RESULTS

This section presents the results of numerical simulations of the accelerator discussed in the previous section. All simulation results presented in this section not only incorporate realistic resistive losses, but also treat properly the effects of the resultant temperature rise on material properties.

Figs. 3 through 5 shows the result of simulating a 30-stage, wound armature launcher. The pertinent system parameters are given in Table 1. As indicated in the figures, an impressive velocity of over 2,200 m/s was achieved, and the acceleration profile shows an excellent average-to-peak acceleration ratio. Note that in Fig. 4 the "active barrel coil" current profile refers not to the current in a single coil but to the current in coil that is producing the primary force on the armature at any given instant.

Fig. 3. Velocity and temperature profiles

Fig. 4. Current profiles

Fig. 5. Acceleration profile

Numerical simulation makes consideration of loss mechanisms a simple matter, and the simulation results presented above illustrate several fundamental effects of resistive losses. First, Fig. 4 shows that the armature current drops steadily during the main portion of the launch. This simple consequence of resistive decay has an important effect; it reduces the energy that can be stored in subsequent barrel stages. The following discussion analyzes this effect in detail.

Recall that (6) relates the barrel coil stored energy to the armature stored energy. Barrel coils closer to the muzzle are active later in the launch; the armature energy level has had more time to decay. As a consequence, the barrel coil can deliver a smaller amount of kinetic energy to the armature. Eventually the energy absorbed from additional barrel length ceases to be worthwhile.

The viable maximum barrel length is affected strongly by the armature time constant; longer time constants allow longer launch times and hence longer accelerators. The previous section pointed out that longer accelerators had a higher limiting efficiency, because a smaller amount of energy must be invested in the armature in order to properly off-switch the barrel coils. Furthermore, reducing the amount of energy that must be stored in the armature reduces the stresses associated with the armature magnetic field. These stresses have been important limiting factors in all designs studied to date.

Because of the interplay of armature current decay and the efficiency and stress advantages of a longer accelerator, there exists an optimum barrel length for a given system. As accelerator length (and hence launch time) is increased, the

Table 1. Pertinent system parameters

Number of Stages	30
Stage Separation (cm)	8
Accelerator Length (m)	2.4
Barrel Coils:	
Inner Radius (cm)	6
Outer Radius (cm)	9
Length (cm)	12*
Material	copper
Packing Factor	0.6
Armature:	
Inner Radius (cm)	4.9
Outer Radius (cm)	5.9
Length (cm)	12
Material	aluminum
Packing Factor	0.6
Mass (kg)	1

* Note stator coil overlap

effects of resistive losses tend to require a higher initial launcher current to reach a given muzzle velocity. However, the effect of the lower stored energy density along the barrel tends to reduce the required armature current. At the optimum barrel length these effects balance, and the maximum velocity possible for a given initial armature current is achieved. The temperature dependence of material properties renders closed-form determination of the optimum length impossible, but iterative simulation readily determines this length for a specific case.

POWER SUPPLY CONSIDERATIONS

Previous sections have studied the operation of the accelerator proper, with no consideration given to the power supply. This section addresses power supply issues, and in particular studies the effect of power supply selection of total system efficiency.

One significant advantage of this type of accelerator is that all launch energy is stored in the system coils prior to the launch. Hence the accelerator serves as its own power conditioning system. In the absence of losses an accelerator could literally be charged from a wall socket, over a period of hours. Losses prevent this, but it is possible to charge the accelerator using a homopolar generator, as the following analysis shows.

Fig. 6 illustrates a lumped-parameter characterization of the homopolar generator-accelerator barrel combination. The homopolar generator behaves as a capacitor, while the accelerator barrel appears as a series R-L circuit. The entire system, therefore, appears as a series RLC circuit. The goal of the charging process is to transfer energy from the capacitor to the inductor, while dissipating as little energy as

possible. It is possible to express this transfer efficiency directly in terms of the component values. In fact, the transfer efficiency is a function of a single variable, the damping factor D , which is defined as

$$D = \frac{R}{2} \sqrt{\frac{C}{L}} \quad (10)$$

The system described in Table 1, when charged using the 60 MJ Balcones Homopolar Generator system, achieves an overall system efficiency (kinetic energy divided by initial generator energy) of approximately 28%. Though low compared to the accelerator efficiency of 89%, this figure compares favorably with the total efficiency of railgun systems.

It is important to emphasize that the transfer efficiency is critically dependent on power supply selection, and that exploitation of the accelerator's ability to serve as its own power conditioning system represents a tradeoff with efficiency. To improve efficiency it is desirable to charge the accelerator as quickly as possible; to exploit self power

conditioning it is desirable to charge the accelerator over a long period of time. How this tradeoff is made is a programmatic decision that cannot be decided in an analytical manner. Analysis serves merely to predict the impact of any particular tradeoff.

CONCLUSIONS

This paper has presented a theoretical discussion of and simulation results for the accelerator currently under development at CEM-UT and discussed power supply issues related to this machine. This accelerator is a complex device the design of which is influenced by a large number of interrelated factors. Some of these factors are addressed in other papers being presented at this symposium.

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REFERENCES

1. D.C. Brate, "Electromagnetic accelerator systems," report no. 57GL 127, General Electric, Schenectady, NY, November 1957.
2. P. Mongeau, "Analysis of helical brush commutation," *IEEE Transactions on Magnetics*, vol MAG-20, no. 2, March 1984, p 231.
3. K. Thom, J. Norwood, "Theory of an electromagnetic mass accelerator for achieving hypervelocities," Langley Research Center, NASA, June 1961.
4. H. Kolm, "Electromagnetic launcher and guns - phase I final report of the MIT group," Mass. Inst. of Tech., June 1981.
5. W. Snow, "DNA solenoid performance analysis," 2nd Symposium on Electromagnetic Launch Technology, Boston, MA, DARPA/AMCCOM, Oct. 1983.
6. P. Mongeau, F. Williams, "Helical rail glider launcher," *IEEE Transactions on Magnetics*, vol. 18, no. 1, Jan. 1982.

Fig. 6. Lumped-parameter characterization of system