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Comparison between Linear Electromagnetic Accelerators

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For symmetric Taylor tests a 2 m long electromagnetic accelerator will be used to accelerate 100 g rods up to 300 m/s. Only a small variance of the muzzle parameters, velocity and exit time, is tolerable. In order to find the most reliable, simple and efficient accelerator type, an axial coilgun, a flat-channel accelerator and an augmented railgun are compared using a lumped parameter model. In particular, the accelerator mutual inductances and their gradients characterize the propulsive forces. The essential advantages of the flat-channel geometry over the axial coilgun geometry are shown. The geometric improvements of the flat-channel accelerator open the way for the augmented railgun suitable and effective for the planned application. To minimize the variance of the muzzle parameters, modular capacitor banks with semiconductor switches allow the dynamic control of the railgun current, in principle.

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1. Introduction

With Taylor tests the mechanical properties of dynamically stressed materials are investigated [1]: A rod with planar ends hits a wall and deforms to a typical shape, giving an estimate of the dynamic material strain rate. Since the wall is not perfectly rigid and since friction losses distort the energy balance an error occurs in determining the stress-strain behaviour. Hence Erlich et al. [2] suggest a Symmetric Taylor Test (STT) in which the rod hits an identical one. Some electromagnetic accelerators (EMA) suit the STT requirements: limited constant acceleration to avoid rod deformation; reproducible impact velocity for the comparison of different experiments. An improvement of the STT is the Complete Symmetric Taylor Test (CSTT): two controlled EMAs are directed towards each other and accelerate the rods at the same time to guarantee an impact located between the muzzles. To find an EMA suitable for a (C)STT, different single-stage EMAs are compared: the axial coil gun (ACG), the flat-channel accelerator (FCA) [3] and the augmented railgun (ARG) [4, 5]. At first specific properties of ACG and FCA (Fig. 1) are compared by using a lumped parameter model. In both systems the externally driven current i_1 in the inductor excites the current i_2 in the armature creating forces F_2 propelling the armature. For FCAs, the movement of the armature is in z-direction. The ACG shown in Fig. 1b works similar except that the armature moves in the x-direction. For direct comparison a square-shaped geometry is chosen rather than the usual circular geometry.

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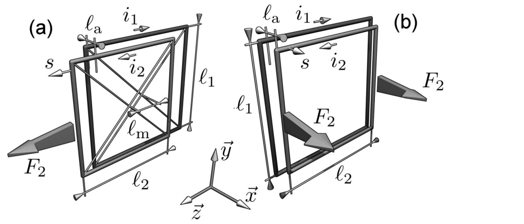

Fig. 1. (a) Sketch of the FCA. (b) Sketch of the ACG.

2. Force and energy formulae

The square-shaped inductor has the side length $\ell_1 = 100$ mm and $\ell_2 = 98$ mm is the armature's side length. The conductors' circular cross section is 1 mm in diameter. For the ACG the centres of the inductor and of the armature coincide. The initial position is $\ell_a = 1.5$ mm. s describes the movement of the armature. For the FCA the conductors keep a distance $\ell_a = 1$ mm in the x-direction. The armature moves in the z-direction, ℓ_m being the distance between both mid-points in this direction. The inductance of the inductor and of the armature is L_1 and L_2 respectively, the mutual inductance is given by M_{12}. Inductance formulae are taken from [6]. The magnetic coupling is expressed by $k = M_{12}/(L_1 L_2)^{0.5}$ and varies between -1 and $+1$. To get the same energetic efficiencies ACG and FCA have the same initial k [7]. To obtain the same initial $k = 0.68$, the armature moves by 2.18 mm in z-direction and s is set to zero. Ohmic losses are neglected. The inductor is initially charged with i_1 ($s = 0$). Thus the upper limits in terms of acceleration and kinetic energy transformation are investigated. Lenz's rule gives

$$i_2 = -\frac{M_{12}}{L_2} i_1. \tag{1}$$

Applying (1), the energy stored in the magnetic field yields

$$E_{\mathrm{mag}} = i_1^2 \frac{L_1}{2}(1 - k^2). \tag{2}$$

With Lenz's rule, $i_{1,0}L_1 = L_1 i_1 + M_{12} i_2$ gives the primary current

$$i_1(s) = \frac{i_{1,0}}{1 - k^2(s)}, \tag{3}$$

where $i_{1,0}$ denotes the current in the inductor when the armature is absent and $k = 0$. Inserting (3) into (2) gives

$$E_{\mathrm{mag}}(s) = i_{1,0}^2 \frac{L_1}{2} \left[\frac{1}{1 - k(s)^2}\right]. \tag{4}$$

The force accelerating the armature is given by $F(s) = -\nabla E_{\mathrm{mag}}(s)$ and yields:

$$F(s) = -\frac{i_{1,0}^2 L_1 k(s)}{[1 - k(s)^2]^2} \frac{\mathrm{d}k(s)}{\mathrm{d}s}. \tag{5}$$

3. Comparison

The relative force $f_{\mathrm{rel}}(s) = F(s)/(i_{1,0}^2 L_1)$ is shown in Figs. 2a and b. Figure 3 shows the functions of the coupling factor dependent on s.

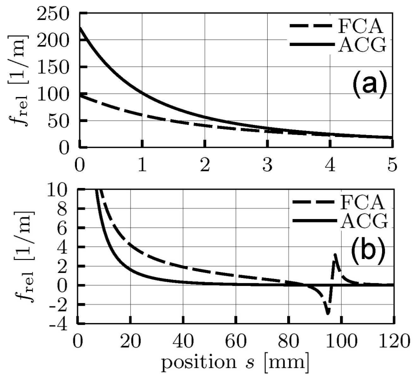

Fig. 2. (a) Relative force acting on the armature at different positions (detail). (b) Relative force acting on the armature at different positions.

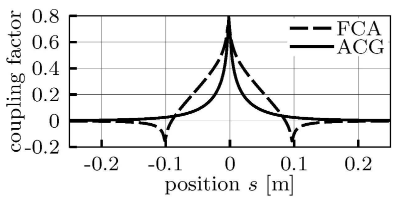

Fig. 3. Coupling factor of the FCA and the ACG depending on the position.

For the same initial primary current the force of the ACG is much higher than that of the FCA on the first 5 mm. By contrast the FCA keeps a higher acceleration

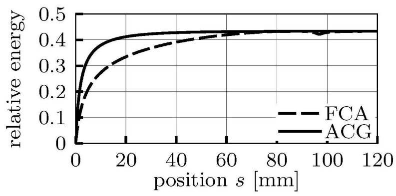

Fig. 4. Relative kinetic energy of the armature.

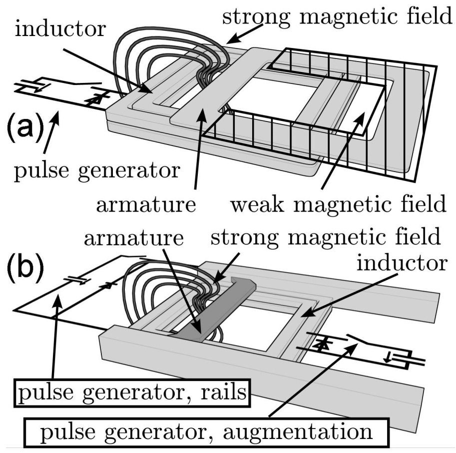

Fig. 5. (a) Sketch of an FCA. (b) Sketch of an ARG.

level when the armature moves by more than 10 mm. The integral of this relative force over the covered distance gives the relative kinetic energy e_{rel} at the position s_{end}

$$e_{\mathrm{rel}}(s_{\mathrm{end}}) = \int_0^{s_{\mathrm{end}}} f_{\mathrm{rel}}(s)\mathrm{d}s. \tag{6}$$

Figure 4 shows e_{rel}. Both cases reach the identical final value. Figure 2a shows that the initial force of the ACG is higher than that of the FCA. Hence the FCA outlined in Fig. 5 shows a better performance at a given acceleration limit. As the B-field is much stronger inside the coil than outside it, the back side of the armature produces most of the force. This is represented by the plain area in Fig. 5a. The only function of the striped area is to allow the circulation of the current. If the armature only consists of a single conductor with sliding contacts the arrangement equals an ARG with the inductor serving as an augmenting coil (Fig. 5b). This decreases the parasitic mass of the armature to 1/4 compared to the FCA. There are additional advantages: Constant rail and armature currents yield a constant acceleration. Capacitors with semiconductor switches as used in the PEGASUS facility [8] allow controlling the acceleration, in principle. This control is easier than with ACGs or FCAs.

4. Discussion and outlook

In principle the FCA and the ACG show the same performance under identical initial conditions. However, for a given limit of acceleration FCAs show better performances. Improving the FCA immediately leads to the

ARG with an essential decrease in the parasitic mass of the driving armature. Therefore, ARGs appear to be best suited for any of processes requiring a strong but limited and continuous acceleration such as the (C)STT. Furthermore, single-stage FCAs and ACGs have finite acceleration lengths, whereas the better controllable ARGs do not have this disadvantage, in principle. For the (C)STT an ARG will be used to accelerate 100 g rods up to 300 m/s. Slide contacts developed at ISL will guarantee the proper passage of the current through the rails into the armature.

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