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DESIGN OF A 20 MJ COAXIAL GENERATOR*

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ABSTRACT. A design is presented for an explosive-driven sweeping-wave coaxial generator. The generator is required to deliver 20 MJ to a 10-nH load with a final current-doubling time of 10 μs. A simple model of the armature motion takes into account both the explosive drive and the back pressure of the magnetic field. Shock and diffusion losses are combined in a self-consistent manner with the armature dynamics to give a circuit model for the generator. The scaling of this design to higher energies is discussed.

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1. INTRODUCTION

This paper summarizes the modeling and design of an explosive-driven sweeping-wave coaxial generator. The generator was designed to deliver 20 MJ of electrical energy to a 10-nH load. It was designed to be relatively fast, with a final current doubling time of order 10 μs, and reasonably efficient, with a high-explosive (HE) to electrical-energy conversion of a few percent.

All explosive-driven generators trade off speed with efficiency and cost. Generators can be made very fast by using excessive amounts of HE to overwhelm the magnetic loading on the armature and by precisely machining armature and stator surfaces for high reproducibility, as was done by Shearer et al. [1]. Alternatively, generators can be made very efficient by using little HE and accepting slow armature motion, as was done in some instances by Sakharov et al. [2].

The design choices described in the following sections were guided by the requirement to achieve a final current doubling time of order 10 μs at low cost, with efficiency being of secondary importance. Section 2 presents some of the considerations used in choosing the materials, shapes, and dimensions of the armature, stator, and inertial tamper. Section 3 describes the circuit model used in the design. The model includes armature dynamics and magnetic field loading in the time-dependent generator inductance, effective resistances and inductances of shock and electromagnetic losses, and a static load inductance. The numerical code used to optimize the generator design is outlined in Section 4. The code
solves the circuit model equations self-consistently with armature dynamics and wall losses. The generator design, including the optimized stator shape and predicted generator performance, is presented in Section 5. Section 6 describes a scaling system that can be used to scale this class of coaxial sweeping-wave generator to higher or lower energies. Conclusions are presented in Section 7.

2. DESIGN CONSIDERATIONS

A schematic of a coaxial sweeping-wave is shown in Fig. 1. This variant has an internal armature and external stator. An initial current is supplied through the annular input slot at the left. The HE is detonated from the left end. The armature expansion, which is primarily radial, progresses to the right as a sweeping-wave following the detonation front in the HE. When the armature first contacts the stator at the input slot, it shorts the generator and isolates it from the current source. The expanding armature compresses magnetic flux between the conductors and drives the flux into the load through the annular output slot at the right.

The generator for our requirements was chosen to be coaxial to reduce the complexity and the inductance of the input and output couplings and to simplify the vacuum system [3]. Coaxial generators are also known for their high current-carrying capabilities and for their ruggedness. The current-carrying capability is limited by the circumference of the inner conductor. Coaxial generators are rugged because both conductors form closed surfaces at contact and can sustain high magnetic pressure.
The armature was chosen to be internal rather than external to reduce the cost of the HE fabrication and initiation system. Lower cost of fabrication is also the reason for choosing the shape of the armature to be a simple cylindrical block at the sacrifice of the higher efficiency of a shaped armature.

The minimum radius of the armature is set by two constraints. The armature should contain enough HE to expand without being substantially decelerated by the magnetic pressure against it. The priority of speed over efficiency dictates this condition. The armature should also have a large enough radius that the current density does not exceed 1 MA/cm. This condition helps to ensure that flux diffusion losses do not become unacceptably large and that deformation of the stator can be managed with reasonable inertial tamping. Twenty megajoules into a 10-nH load implies both a final current of 53 MA and a minimum radius of at least about 10 cm. The radius must also be large enough that the long foot of the current feed pulse into the generator does not increase the armature temperature beyond the point at which performance is affected.

The minimum length of the armature is set by the required energy multiplication. Assuming no losses, the theoretical energy and current multiplication is

\[ \alpha = 1 + \frac{L_{g0}}{L_L} \]

where \( L_{g0} \) is the initial generator inductance and \( L_L \) is the load inductance. Owing to losses, the actual energy multiplication is closer to
a/2. Because $L_\text{go}$ scales approximately with the length of the generator, so does the energy multiplication.

As the armature length of this class of generators is increased, however, the generators tend to become less efficient. Because losses are integrated over area and time, they tend to be lower in short generators. Also, in short generators, a greater fraction of the armature is in motion and contributing to flux compression during the critical final current doubling time.

The high-performance explosive PBX 9501 was selected as the HE for the generator because of its high detonation velocity of 0.88 cm/µs [4]. The high detonation velocity is needed for generator speed. The annular conductor about the HE was chosen to be fully-annealed 6061 aluminum for two reasons. Armature tests have demonstrated that a cylinder of 6061 Al can conservatively be expected to expand to 2.5 times its initial radius without appreciable cracking if the thickness-to-radius ratio is at least 0.1. Also, although both shock and electromagnetic losses are higher in aluminum than in a better conductor such as copper, the lighter density of aluminum allows a faster armature expansion for a given thickness of conductor and makes a faster generator.

The stator material was chosen to be copper, because higher density and higher conductivity are both advantageous in a stator. However, the greater ease and lower cost of fabrication of aluminum stators has caused us to consider this alternative, particularly since our calculations show
that the final energy into a load will be no more than about ten percent less for an aluminum stator than for copper.

The annular input slot of the generator is made long enough to allow for some smoothing of asymmetries in the initial armature expansion before the detonation front reaches the main generator cavity. The input cone is canted at 20° from the radial plane to reduce distortion of the shape of the expanding armature and to reduce jetting from the intersection of the input cone with the outer cylindrical wall. The outer cylindrical wall was designed to have a radius 2.5 times the armature radius to provide the most inductance consistent with a conservative armature expansion ratio. The outer cylindrical wall also had to be long enough to support a flange connecting the input and output cones.

The shape of the output cone is one of the most important features of the design, and is discussed further in Section 5. If the angle of the output cone is much shallower than the sweeping wave, the generator will be substantially slower owing to the longer time required to remove the last 10 to 20 mH from the generator. Optimal generator speed is attained when the sweeping wave subtends no more than about 1° with the output cone at the point of contact. A closer fit is not warranted because of flux diffusion into the surfaces.

One way to design the stator shape is to measure the shape of the sweeping wave experimentally in a working generator, and to modify the stator accordingly. This method relies on using sufficient HE to make the altered loading and losses of the corrected stator shape negligible. It
also relies on precision machining giving high shot-to-shot reproducibility. This method, although inefficient and costly, can result in very fast generators [1].

An alternative approach, used here, is to measure the shape of an armature in free expansion without a stator or current, and then to calculate how the shape will be altered by magnetic loading and losses in an operating generator. This approach is described in the next section.

The annular output slot was chosen to lie alongside the armature rather than at some greater radius for three reasons. The output slot, when near the armature, is farthest from any jetting that may occur at the outer wall. Secondly, in this position the output slot is nearest the load and requires the shortest transmission line. Finally, the magnetic field is highest near the armature and provides the best magnetic insulation there.

The generator is evacuated to avoid air shocks and gas breakdown. The voltage across the output slot in the final current doubling is not expected to exceed

\[ V \approx \frac{\Delta LI}{\Delta t} \times (30 \text{ MA} \times 20 \text{ nH})/10 \text{ µs} \approx 60 \text{ kV} \]

At the design peak-current density, a 1-cm slot should be magnetically well insulated for both ion and electron crossings. The output slot is not made too much wider because the additional inductance slows the generator.
Inertial tamping of the external surface of the stator is needed to avoid excessive motion of the stator during generator burn or compression. The thickness of the stator conductor is limited by the complexity and cost of fabrication to about 1 cm. This thickness is insufficient to prevent the stator from moving more than a few millimeters during the burn and degrading performance. The generator design code described in Section 4 has been used to calculate the magnetic pressure against the stator expected during burn as a function of time and position. This information was used to calculate the amount of tamping needed to limit stator motion to the order of millimeters. Lead was chosen as the tamping material because of its malleability, low cost, and high density. It is applied to the stator in staves with a tight fit of the order of 1 mm required. The most tamping is needed near the output end where the pressure is highest and is exerted for the longest time.

3. CIRCUIT MODEL

The circuit model used to design the generator includes armature dynamics because the changing shape of the armature determines the generator inductance. The current must be calculated self-consistently with the armature motion to predict magnetic loading and losses, which are also included in the circuit model.

A sequence of framing camera photographs, several of which are shown in Fig. 2, was obtained from a case expansion shot and used to determine the free expansion of the armature needed for the generator design.
free expansion was observed to be almost radial with a radial acceleration of the form

\[ \ddot{r}_f(t,z) = \delta_0 (v_d t - z) \left[ v_0 \delta(t-z/v_d) + (v_1/T) \exp(-t/T) \right] , \quad (1) \]

where \( \delta_0 \) is a step function describing propagation along the longitudinal or z direction of a detonation wave at velocity \( v_d \). The \( \delta \) function describes an impulsive initial acceleration. The parameters \( v_0 \), \( v_1 \), and \( T \) are constants. The detonation velocity of PBX 9501 is \( v_d = 0.88 \text{ cm/\mu s} \). The asymptotic velocity of the expansion \( v_0 + v_1 \) is taken to be the Gurney velocity \( v_G \).

The Gurney velocity of a cylindrical block of HE having a Gurney energy \( E \) and a mass \( C \) and surrounded by a metal cylindrical shell having mass \( M \) is [5]

\[ v_G = \left[ \frac{2E}{\left( \frac{1}{2} + \frac{M}{C} \right)} \right]^{1/2} . \]

For PBX 9501, \( E = 4.3 \text{ MJ/kg} \). For the design shown in Fig. 1, \( C = 80.0 \text{ kg} \) and \( M = 25.4 \text{ kg} \). The Gurney velocity is, therefore, \( v_G = 0.325 \text{ cm/\mu s} \). The best fit to the case expansion shot was found for

\[ v_0 = 0.10 \text{ cm/\mu s}, \quad v_1 = 0.225 \text{ cm/\mu s}, \quad \text{and} \quad T = 8 \text{ \mu s} . \]
In the generator, the armature is decelerated by magnetic pressure. The deceleration from magnetic loading,

$$\tau = \frac{-v_{G}^{2}}{r}(I/I_{c})^{2},$$

depends on armature radius $r(t)$ and current $I(t)$ normalized to $I_{c} \equiv (8\pi CE/\mu_{0} t)^{1/2}$, where $t$ is the armature length. The acceleration of a loaded armature,

$$\ddot{r} = \ddot{r}_{f} + \ddot{r}_{L},$$

must be found self-consistently from the time-dependent current in a circuit model.

The circuit representing generator and load after the feed-current source has been isolated is shown schematically in Fig. 3. The circuit equation is

$$(L + R)\dot{I} + (L_{g} + L + L_{f})I = 0,$$

in which $L$ and $R$ are the effective inductance and resistance for shock and electromagnetic losses. From expressions for shock and electromagnetic losses in Knoepfel [6], the effective inductance and resistance are given by

$$L = L_{1} \int r^{-3} dA$$ and

$$R = L_{1} t^{1/2} \int r^{-3} dA$$ (6a)
\[ R = R_1 I^2 \int r^{-4} \, dA + R_2 \int I^2 t^{-1/2} r^{-3} \, dA, \]  

(6b)

where

\[ R_1 = 0.7 \times 10^{-8}, \quad R_2 = 4.0 \times 10^{-6} \quad \text{and} \quad L_1 = 2.4 \times 10^{-5} \]

for a copper surface, and

\[ R_1 = 1.8 \times 10^{-8}, \quad R_2 = 7.5 \times 10^{-6} \quad \text{and} \quad L_1 = 4.5 \times 10^{-5} \]

for an aluminum surface. The units here are cm, MA, µs, mΩ and nH. The integrals are over current-bearing surface areas.

The circuit model comprises Eqs. (1)-(6), which are solved numerically using the code GNDSN to optimize the generator design.

4. GENERATOR DESIGN CODE GNDSN

The design code GNDSN calculates the coaxial generator inductance and current self-consistently with shock and electromagnetic losses and armature dynamics including loading by the magnetic field for any arbitrary axially symmetric armature and stator shapes.

The code calculates only radial motion \( r(z,t) \) of the armature in each of \( n \) (typically \( n = 181 \)) zones along the axis according to Eqs. (1), (3) and (4). The motion includes the acceleration caused by the HE and the deceleration caused by the magnetic loading. The radial expansion is
calculated only in those zones from the point of contact of the sweeping wave with the stator to the detonation front. The sweeping wave advances radially and the phase (detonation) advances axially with each time step.

As in Fig. 3, the circuit consists of a generator inductance, a load inductance, and an effective inductance and resistance caused by shock and electromagnetic losses. The resistance and inductances are calculated self-consistently with the armature shape and current at each time step. Shock and electromagnetic losses are integrated over the entire current-bearing area inside the generator, including the deformed armature surface.

The code pauses and reads out the shape of the sweeping wave when any flux trapping occurs, so that the stator surface can be corrected for the next run. Through this iterative process, the stator shape has been optimized within the constraints imposed by the design considerations of Section 2.

5. GENERATOR DESIGN

An armature length of 100 cm and outer diameter of 25 cm were chosen. The dimensions were chosen partly for the convenience of having prefabricated sections available, but more importantly because this size has sufficient energy to dominate magnetic loading and losses and to achieve a fast output of the required energy.
The stator shape was optimized for this armature using the design code GNDSDN. The stator consists of five sections as shown in Fig. 1—an annular input slot, an input cone, an outer cylindrical wall, an output cone, and an annular output slot.

The annular input slot was chosen to be 10 cm long to allow for some attenuation of shocks and asymmetries before the sweeping wave reaches the main cavity. The input cone is given a half angle of 70° and is limited in height to 2.5 times the armature radius, or 63 cm i.d., to avoid cracking during armature expansion. The outer diameter of the annular output slot was chosen to be 3 cm greater than the armature to provide adequate magnetic insulation.

The lengths of the outer cylindrical wall and output slot and the shape of the output cone were selected by an iterative optimization process. First the length of the outer cylindrical wall was chosen such that the sweeping wave reached the end of it shortly before the detonation front reached the end of the armature. Then in a three-parameter optimization, the length of the throat was chosen together with the shape of the output cone to avoid flux trapping and to get maximum energy output before the sweeping wave reached the end of the armature. The output cone was chosen in the parameterization to be a linear superposition of a straight line connecting left and right boundaries and a truncated Fourier series consisting of only a half sine wave and full sine wave of variable amplitudes.
The optimal design was found for an outer cylindrical wall length of 25 cm, an output slot length of 5 cm, and half sine and full sine wave amplitudes of -0.3 cm and 0.3 cm, respectively. The predicted current waveform in the load from armature detonation to burnout is shown in Fig. 4. The initial inductance of the generator without load is 112 nH. The generator has been overdesigned in that the code predicts a final energy of 36 MJ into the load with a final current doubling time of 13 μs. Figure 4 also shows the higher current predicted by the code if shock and electromagnetic losses are ignored.

Because the optimal wall shape of the output cone is nearly straight, the final energy of 33 MJ predicted for straight walls is sufficiently close to the optimal energy that the greater ease of fabrication warrants straight conical walls. Similarly, an aluminum stator with a straight output cone is expected to deliver 30 MJ to a load, and appears warranted in future applications because of significantly easier fabrication.

A schematic of the final generator design including initiator and load is shown in Fig. 5.

6. SCALING SYSTEM

Some physical insight into the class of coaxial sweeping wave generators to which the example described here belongs can be gained by scaling the generator in energy. In the scaling system we wish to maintain as invariants relative distances (and shapes), velocities, loading, and energy multiplication. The only self-consistent scaling that maintains
these quantities as invariants has the following form (in which x is the scale factor by which, for example, all lengths are scaled).

\( x^0 \) : Quantities remaining invariant

- Energy multiplication (and current multiplication)
- Gurney velocity
- Detonation velocity
- Armature expansion velocity
- Loading
- Current width
- Magnetic field
- Gurney angle (and shape of expanding armature)
- Gurney specific energy
- \( r_{\text{stator}}/r_{\text{armature}} \) - expansion ratio
- \( C/M \) - mass ratio of HE to conductor in armature

\( x^1 \) : Quantities scaling linearly

- Lengths
- Inductances of generator and load
- Current
- Current normalization
- Time scale (burn time, doubling time, etc.)
- \( d(LI)/dt \) - voltage

\( x^2 \) : Quantities scaling quadratically

- Areas
$x^3$ : Quantities scaling cubically
- $r^2l$ - volume
- $C,M$ - masses of HE, conductor
- $LI^2/2,CE$ - energies

$x^{-1}$ : Quantities scaling inversely
- $f$ - acceleration

The generator scales well. Without losses a scaled generator would reproduce the shape of the expanding armature. However, shock energy loss per unit area scales as

$$W_{sh} \sim (I/r)^4 t \sim x^3$$

and electromagnetic (flux diffusion) energy loss per unit area scales as

$$W_{em} \sim (I/r)^3 t^{1/2} \sim x^{3/2}$$

Because energy scales as $x^3$, but energy losses scale as $x^3$ and $x^{5/2}$, the losses are relatively larger in smaller generators and smaller in larger generators. This means that scaling to larger generators appears favorable, but that scaled-down experiments may be of limited usefulness. Because the scaling of energy losses does not correspond with the scaling of generator energy, the scaling gives only the gross features of a new design. The design code is used for fine tuning.
7. CONCLUSIONS

We have summarized the steps leading to the design of an explosive-driven coaxial sweeping-wave generator required to deliver at least 20 MJ to a 10 nH load with a final current doubling time of order 10 μs. The steps include: basic physical considerations of configurations, materials, armature dynamics, magnetic loading, shock and electromagnetic losses, and insulation; case expansion shots to determine free armature expansion; self-consistent modeling of the generator circuit and generator dynamics by a design code; and matching by the code of the stator shape to the sweeping wave to avoid flux trapping and optimize speed and energy output. The generator design is representative of a class of generators, which may be scaled to higher or lower energies.
REFERENCES


FIGURES

Figure 1. Schematic design of coaxial sweeping-wave generator optimized by the design code GNDSN.

Figure 2. Framing camera photographs from free expansion shot of design armature (PBX 9501, 22.86-cm diameter; fully annealed 6061 Al, 25.14-cm o.d.). Top view was taken at mid-frame time of 56.3 μs after HE initiation; bottom view at 98.3 μs.

Figure 3. Schematic of generator and load circuit after isolation from current source. L₁ and L₂ are generator and load inductances. L and R are effective inductance and resistance of shock and electromagnetic losses.

Figure 4. Predicted current into 10 nH load versus time from detonation for optimal generator design both with and without shock and electromagnetic losses according to design code GNDSN.

Figure 5. Final design of coaxial sweeping-wave generator including initiator and load.
INCLUDING LOSSES

WITHOUT LOSSES