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MASTER**SMALL HELICAL FLUX COMPRESSION AMPLIFIERS**

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ABSTRACT

Small, explosively compressed, magnetic flux transducers with many closely spaced helical turns are investigated theoretically and experimentally. The analysis is limited to linear operation, but takes into account load influence, proximity effects, and switching delays. The latter are due to retarded breakdown in the wire insulation and to the finite decay time of the magnetic field in the wire.

More than 150 experiments showed considerable data scatter. Shots which exhibited low clocking and high amplification were in good agreement with the theory. The main conclusion is that device performance is limited not only by flux loss, but by flux remaining in the generator after compression.

I. INTRODUCTION

We are concerned with the physics of small ($\sim 100 \text{ cm}^3$) compressed magnetic flux (CMF) current amplifiers in which an armature is expanded by the detonation of an explosive into a closely wound coil with as many as 100 turns of thin (1 mm or less) wire. Our transducers are at the very low energy output extreme (a few hundred joules) of the many variations of CMF arrangements treated in the extensive literature¹.

They differ from the more common larger helical compressor amplifiers (such as e.g., reported by Crawford and Damerow²) by the closeness of turns, by the higher wiping velocity of the contact, and by the higher inductances acceptable as loads. A modification of elementary generator theory is required.

The analysis of the small CMF amplifiers will be based on an equivalent circuit model. It is complicated by the necessity to include, in addition to load resistance, R_L , and load inductance, L_L , eight basic design parameters (dimensions, conductivity σ , expansion velocity u) and time t . Difficulties are introduced by an insulating layer between armature and coil with a delayed breakdown, which prevents us from assuming simply an ideal short circuit moving along the coil.

A related modification is demanded by the fact that the contact point moves with very high circumferential speed along

the wire (1/2 percent of light velocity). Because the magnetic field stored in the skin layer has a finite decay time, considerable inductance is still left in the circuit behind the moving contact.

To make possible a general analytic description of the flux compression process taking 11 parameters into account, approximations have to be introduced: (1) The current on the armature surface is assumed to be a mirror image of the coil current. (2) The analytical model is limited to the linear, i.e., low current case. (3) Capacitances are neglected. (4) Dependence of skin layer thickness and flux decay on time are linearized. (5) End and size effects are covered by a generalized Nagaoka correction. (6) The proximity effect between coil wires is taken into account, the one between coil and armature is estimated.

II. SYSTEMS EQUATION

The compressed magnetic field generator is sketched in Fig. 1. A coil of length b with N turns of wire (diameter d , turn spacing c , conductivity σ) has an inner radius of a_1 . A current I_0 is flowing through the coil and load (L_L, R_L) and short circuited at time $t = 0$ by the expanding armature, which in a time interval t_c wipes all the coil turns. The "ground wire" current return adds an inductance that is initially about 8 nHy and decreases to zero at the end of generator operation. This contribution will be neglected. This permits us to assume for purposes of analysis that the return current flows on the armature. We also neglect the time

FIG. 1: SCHEMATIC CROSS-SECTION OF CMF AMPLIFIER
CONTAINING N TURNS WHERE $N = b/c$.

dependence of L_L , but not of R_L . Neglecting capacitances, our arrangement is a series circuit of inductances and resistances which obeys the circuit equation,

$$\frac{d}{dt} (LI) + IR = 0 ; \quad (1)$$

where L is the total series inductance, R the total series resistance, and I the current. The initial condition is that $I = I_0$ at time $t = 0$. The differential equation (1) may be solved rigorously to yield the integral equation

$$\frac{I(t)}{I_0} = \frac{L(0)}{L(t)} \exp \left\{ - \int_0^t \frac{R(T)}{L(T)} dT \right\} ; \quad (2)$$

where $L(0)$ is the initial series inductance at crowbar time. The difficulty with Eq. (2) is the complexity of the functions $L(t)$ and $R(t)$. Basically, R and L depend on skin depth δ , which in turn depends on $I(t)$. We solve for $I(t)$ by approximating L and R , using the best available analytic expressions³. The analysis will be only sketched here; it has been treated in detail elsewhere⁴.

It is convenient to introduce a few parameter combinations to simplify the analytic descriptions. We define a magnetic Reynolds number as the product of the induction constant μ ,

the conductivity σ , the average radial velocity u , and the initial armature spacing S , i.e.,

$$R_m = \mu \sigma u S . \quad (3)$$

If the current would rise exponentially in time as $\exp(t/t_c)$, where t_c is the compression time, the flux skin depth would be (Ref. 1, p. 55, and considering that $ut_c = S$)

$$\delta_o = \sqrt{\frac{t_c}{\mu \sigma}} = \frac{S}{\sqrt{R_m}} . \quad (4)$$

Our actual skin layer depth, $\delta(t)$, can be approximated linearly over the compression time by

$$\delta(t) = \frac{\delta_o}{\sqrt{2}} (1 - \Gamma \tau) \quad (5)$$

where Γ is the slope of the decrease, and $\tau = t/t_c$. Eq. (5) is justified in Ref. 4.

Before we establish $R(t)$ and $L(t)$, we shall discuss the delay phenomena which contribute to both these functions.

III. FLUX DELAY PARAMETERS

As stated, there is a very thin insulating sheet (~50 microns) on the inside of the coil. In many of our generators it takes the shockwave that is generated by armature impact

about 20 nsec to traverse the insulating layer. After this time, compression at the location of impact is essentially terminated. As Graham⁵ has found, however, it takes much longer for the insulators investigated to break down electrically; we call this delay time t^* .

In Fig. 2A, a highly simplified bellows type, two-dimensional CMF arrangement is shown for illustration. H is perpendicular to the paper, and a current I flows in the skin layer of thickness δ around the circuit. At time t_1 the armature impaction point, moving with a velocity v , has reached location x_1 . The breakdown point between the metal electrodes is, however, set backwards by a distance

$$e_1 = vt^* \quad , \quad (6)$$

and the flux contained in the area $2e_1\delta$ is kept in the circuit.

An additional delay length, e_2 , is introduced by the fact that a magnetic field takes a finite time t' to decay, and commensurable time is needed to change the original current path. As indicated in Fig. 2B, where we use the linearized decay approximation, the current will gradually turn around over a length $2e_2 = vt'$, with the average length added to the current path being

$$e_2 = vt'/2 \quad . \quad (7)$$

FIG. 2: VARIOUS PHASES OF OPERATION OF A PLANAR CMF GENERATOR. (A) ILLUSTRATION OF COMPLETE GENERATOR SHOWING THE LOCATION P OF INSULATOR BREAKDOWN LOCATION. (B) ILLUSTRATION OF MAGNETIC FIELD DECAY BEHIND BREAKDOWN POINT. (C) END STATE AT $t = t_c$.

There is at present no way to calculate t' accurately for our complicated wire-coil geometry. For the linear model in Fig. 2 we obtain (See Ref. 4),

$$t' = \mu \sigma \delta^2 / 3, \quad (8)$$

which we will use as an approximation. The delay times, t^* and t' , and with them the delay lengths e_1 and e_2 , turn out to be of the same order of magnitude. From their definitions t^* is strongly dependent on materials' properties, t' on temperature.

Figure 2C is shown to illustrate that at the end of compression the inductance determining area $2\delta(e_1 + e_2)$ is small compared to the inductance area of the load. For bellows type and concentric flux compressors the delay effect is very small. For our coil generators, however, the delay length $e = e_1 + e_2$ can contain many turns. The resulting remaining generator inductance determines the limit of amplification for the case of small load inductances.

The end of compression (Fig. 2C) signifies end of electrical energy addition to the system. It does not mean the end of inductance change, as the breakdown distance is reduced linearly to zero over a time t^* . Equation (1) still applies; it does not lead to noticeable amplification, however, as R/L has meanwhile become very high, and the skin layer is expanding instead of contracting. We will neglect post-amplification (See Ref. 4).

IV. THE RESISTANCE AND THE INDUCTANCE FUNCTIONS

The resistance $R(t)$ is the sum of the coil and the load resistance, $R_C + R_L$. (Fig. 2).

It is shown in Ref. 4, that a good approximation for the resistance is

$$R(t) \approx 2 \left(\frac{8a_1}{\sigma d} \right) \left(\frac{3f}{2} \right) \left(\frac{d}{4b} \right) \left(\frac{b}{c} \right) \left(1 - \tau + \frac{t^*}{t_c} + \frac{t'}{2t_c} \right) + R_L. \quad (9)$$

The first factor, 2, takes into account doubling of the coil resistance by the mirror current on the armature.

The second, third, and fourth factor is the single turn d.c. resistance, the proximity factor, and the skin effect correction. For the total number of turns we have written b/c instead of N . The linearly decreasing time function carries the delay terms from Eq. (6) and (7), respectively. The symbols have been introduced before except for f , the turn-to-turn proximity factor (See Ref. 3, p. 56), which is enhanced here by an averaged armature proximity correction $3/2$, justified in Ref. 4.

We now introduce Eqns. (4), (5) and (8) into (9) and write for the sum of coil and load resistance

$$R(t) = \left[\frac{6\sqrt{2}fa_1b}{\sigma dc\delta_o} \right] \frac{\left(1 - \tau + \tau^* + \frac{(1 - \Gamma\tau)^2}{12} \right)}{(1 - \Gamma\tau)} + R_L; \quad (10)$$

where we have written τ^* for t^*/t_c , the normalized delay

time for insulation breakdown. At the end of compression, $\tau = 1$, there is still considerable resistance in the coil.

Generally, (See Fig. 1) the armature consists of a conical and a cylindric part. Fortunately, for the devices we are considering, the cone is so long due to the low angle α (11° to 14°), that after the device has crowbarred at time $t = 0$, the armature cone extends to the end of the coil, and we have to consider only a conical geometry.

We assume that the contact point between armature and coil moves with constant axial velocity, v , and the cone angle α is also constant, neither statement being strictly true. It has been observed that the average cone angle α is larger, if the end distance S (at $t = 0$) between armature and cone is larger. We therefore choose (See Fig. 3)

$$\tan \alpha = \frac{S}{b_1}, \quad (11)$$

where b_1 is the crowbar point distance from the end of the coil and slightly larger than the coil length b .

The coil in Fig. 3 is assumed wound of rectangular wires, separated by infinitely thin sheets of ideal insulation (sheet model). At the time t the magnetic field in the wire reaches uniformly to a depth $\delta(t)$. A current I flows in the sheet, and the magnetic field on the surface of coil (and armature), H , is therefore I/c .

FIG. 3: SCHEMATIC OF COIL-ARMATURE ARRANGEMENT AT TIME $t = 0$ AND $t = t$, WITH $x_0 = vt$. GEOMETRY IS BASIS FOR INTEGRATION OF EQ.(12).

If in actuality, the wires of the coil are round, spaced, and some insulation is to be accounted for, we add a factor k to the value of the volume in which lost flux is stored. The factor k is about 1.1 to 1.2 for tightly wound coils and larger for widely spaced turns.

To calculate L , we use the energy definition of L

$$\frac{1}{2} LI^2 = \frac{1}{2} \int \mu H^2 dV, \quad (12)$$

where dV is the volume element, proportional to dx in Fig. 3. Introducing a modified Nagaoka correction factor (See Ref. 3, p. 42), $[1 + 0.9(1 - \tau) \tan \alpha]^{-1}$, we find after integration for $L(t)$:

$$L(t) = \left[\frac{\mu \pi a_1 b_1 S}{c^2} \right] \left[\frac{1}{1 + 0.9(1 - \tau) \tan \alpha} \right] \\ \times \left\{ (1 - \tau)^2 \left[1 - \frac{S}{3a_1} (1 - \tau) \right] + k \sqrt{\frac{8}{R_m}} (1 - \tau) \right. \\ \left. \times \left[1 - \tau + \tau^* + \frac{(1 - \tau)^2}{12} - \frac{S}{4a_1} (1 - \tau)^2 \right] \right\} + L_L. \quad (13)$$

The first term in the curved bracket represents the contribution of the field between coil and armature, decreasing

essentially as $(1 - \tau)^2$. The second term is due to the flux in the skin layer, decreasing less fast and producing a finite remaining inductance at the end of compression.

V. CURRENT AMPLIFICATION RELATIONS

With $L(t)$ and $R(t)$ now established, we can write down the solution to our basic performance Eq. (2). We will split the result into three physically meaningful factors:

- 1) The compression amplification

$$A = \frac{L(0)}{L(t)} \quad (14)$$

- 2) The flux loss correction due to losses in coil and armature

$$B = e^{-\int \frac{R_c}{L} dt} \quad (15)$$

where R_c is the coil resistance, the first part of Eq. (10), and

- 3) the losses due to the load resistance R_L ,

$$C = e^{-\int \frac{R_L}{L(t)} dt} ; \quad (16)$$

with A , B , C being functions of time, we will have

$$\frac{I(t)}{I_0} = ABC . \quad (17)$$

While the integrals in the exponent, after introduction of (10) and (13), may be computer integrated, it appears desirable to simplify $R(t)/L(t)$ in such a manner that the integrals can be expressed by common analytic functions. We shall replace in the quotient R/L the corrective minor terms (such as $(1 - \Gamma\tau)^2/12$) by their end compression values, keeping the dominant terms intact.

Abbreviating, from (10)

$$R_o = \frac{6\sqrt{2}fa_1b}{\sigma dc\delta_o} \quad (18)$$

and, from (13)

$$L_o = \pi\mu a_1 b_1 S/c^2, \quad (19)$$

yielding

$$\frac{R_o}{L_o} = \frac{6\sqrt{2}fb_o c}{\pi\sqrt{R_m t_o b_1 d}}, \quad (20)$$

we may write

$$\left(\frac{R(t)}{L(t)}\right)_{coll} \approx \left[\frac{R_o}{L_o}\right] \times \left[\frac{1 - \tau + \tau^2 + \frac{(1 - \Gamma)^2}{12}}{(1 - \Gamma\tau) \left\{ (1 - \tau)^2 + k \sqrt{\frac{8}{R_m}} \left[1 - \tau + \tau^2 + \frac{(1 - \Gamma)^2}{12} \right] + 1 \right\}} \right], \quad (21a)$$

where $l = L_L/L_0$, and

$$\left(\frac{R(t)}{L(t)}\right)_{\text{load}} \approx \left[\frac{R_0}{L_0}\right] \times \left[\frac{r}{(1 - \Gamma'\tau) \left\{ (1 - \tau^2) + k \sqrt{\frac{S}{R_m}} \left[1 - \tau + \tau^* + (1 - \Gamma)^2/12 \right] + l \right\}} \right] \quad (21b)$$

where Γ' is the slope of the skin depth decrease in the load, and $r = R_L/R_0$. A calculator study shows that while the functions so simplified differ from their true values substantially (~20%) in the beginning, they approach exact values fast, and have become excellent approximations at closure time. Thus, the integrals themselves, which grow strongly towards the end of compression, are good approximations.

With these simplifications, we obtain finally, with

$$1 - \tau = 1 - t/t_c = x,$$

$$A = \frac{\left[1 + 0.9 \left(\frac{S}{b_1} \right) x \right] \left[\left(1 - \frac{S}{3a_1} \right) + k \sqrt{\frac{S}{R_m}} \left\{ 1 + \tau^* + \frac{1}{12} - \frac{S}{4a_1} \right\} \right] + l}{\left[1 + 0.9 \frac{S}{b_1} \right] \left[x^2 \left(1 - \frac{S}{3a_1} x \right) + k \sqrt{\frac{S}{R_m}} (1 - \Gamma\tau) \left\{ x + \tau^* + (1 - \Gamma\tau)^2/12 - \frac{S}{4a_1} x^2 \right\} \right] + l} \quad (22)$$

Abbreviating

$$a = k\sqrt{8/R_m} \quad , \quad b = k\sqrt{8/R_m} [\tau^* + (1 - \Gamma)^2/12] + l$$

$$\gamma = (1 - \Gamma)/\Gamma \quad , \quad T = \tau^* + (1 - \Gamma)^2/12 - (1 - \Gamma)/\Gamma$$

$$r = R_L/R_O \quad , \quad D = 6\sqrt{2}fbc/2\pi b_1 d \quad ,$$

we find for the coil loss integral

$$\begin{aligned} \ln B = - \int_0^t \frac{R_c}{L} dt = \frac{D}{\sqrt{R_m} \Gamma} & \left\{ \frac{T}{\gamma^2 - a\gamma + b} \ln \frac{(x + \gamma)^2}{x^2 + ax + b} \right. \\ & \left. + \left[\frac{T(2\gamma - a)}{\gamma^2 - a\gamma + b} + 2 \right] \frac{2}{\sqrt{4b - a^2}} \tan^{-1} \frac{2x + a}{\sqrt{4b - a^2}} \right\} \Bigg|_1^{1-t/t_c} \quad (23) \end{aligned}$$

Finally, the load loss integral is

$$\begin{aligned} \ln C = - \int \frac{R_L}{L} dt = \frac{D}{\sqrt{R_m} \Gamma} & \left\{ \frac{r}{\gamma^2 - a\gamma + b} \ln \frac{(x + \gamma)^2}{x^2 + ax + b} \right. \\ & \left. + \left(\frac{r(2\gamma - a)}{\gamma^2 - a\gamma + b} \right) \frac{2}{\sqrt{4b - a^2}} \tan^{-1} \frac{2x + a}{\sqrt{4b - a^2}} \right\} \Bigg|_1^{1-t/t_c} \quad (24) \end{aligned}$$

The solution is valid only for $4b > a^2$; it turns out, that for our geometries this is always the case, if $R_m > 300$. Eqs. (23 through 26) are suitable for programming into a small calculator. Γ is about .55; corrections are discussed in Ref. 4.

Analysis of Eqs. (17), with (22) through (24), reveals a general property of CMF devices: The current amplification, $ABC = I/I_0$, is quite insensitive to many parameter variations over a wide range. The cause is our basic Eq. (2): If $L(t)$ becomes smaller, first term A becomes larger and second term $BC = \exp \left[- \int (R/L) dt \right]$ becomes smaller. This fact limits design improvements, but leads to greater performance stability. It also justifies some of our approximations in retrospect.

The situation is illustrated in more detail in Fig. 4, where the end amplification $I_{\max}/I_0$ is plotted versus Reynolds number. Even for a (theoretically possible) short circuited device ($l = 0$; $r = 0$), the amplification is not proportional to R_m , as simple theory predicts (Ref. 1, p. 187). For reasonable loads ($l = .002$, $r = .02$, corresponding to a 100 nHy flat cable load), $I_{\max}/I_0$ is approximately proportional to $\sqrt{R_m}$. For high loads ($l = 0.02$, $r = .19$, a one microhenry cable), the response is even flatter.

In Fig. 4 some parameter variations are studied. If k is varied 33%, the output varies 17% for the short circuit and only 5% for high Reynolds number devices working into a medium load. On the low Reynolds number side the changes are negligible, as they are for high inductance loads.

FIG. 4: MAXIMUM CURRENT AMPLIFICATION SHOWN AS A FUNCTION OF MAGNETIC REYNOLDS NUMBER FOR VARIOUS LOAD FACTORS l, r . THE SOLID CURVES ARE FOR THE CASES WHERE $k = 1.2$ AND $r = 0.05$.

A change of τ^* or delay length e , [See Eq. (6)] by 20% leads only to an average amplification change by 5% for medium loads - for low inductance loads the change would be appreciably higher, though.

The figure also illustrates a strong influence of the load. The previous statement, that the performance of our transducers is not sensitive to variations in most parameters has to be qualified. It does not, from a certain small threshold up, apply to certain mechanical dimensions, i.e., some of our tolerances are quite severe⁶. Deviations from coil roundness or accurate centering of the armature, e.g., are limited to 25 microns or less for our model, if turn jumping is to be avoided.

VI. MECHANICAL MEASUREMENTS

Most experiments were performed with a "standard" CMF unit, the dimensions of which are listed in Table I. Crowbar buttons were provided as indicated in Fig. 1. A sample of the device is shown in Fig. 5, top, and an x-ray of it on the bottom of this figure.

FIG.5: TOP: EXPERIMENTAL GENERATOR, SURROUNDED BY MODELS OF ARMATURE AT VARIOUS STAGES OF EXPANSION. BOTTOM: X-RAY OF COIL. HORIZONTAL BAR IS PE TIME OF ARRIVAL DETECTOR.

TABLE I

Laboratory Test Unit, Standard

Inner Coil Radius a_1	= 15.25 mm
Outer Armature Radius a_o	= 7.95 mm
Compression Distance S	= 7.30 mm
Wire Diameter (Cu) d	= .40 mm
Wire Center Distance c	= .46 mm
Coil Length b	= 32 mm
Crowbar Point to Coil End Length b_1	= 35 mm
Turn Number N	= b/c = 70
Average Cone Angle α	= 11.5°
Magnetic Reynolds Number, R_m	= 1150

About 200 CMF transducers as described were available, almost all using the same coil and crowbar button arrangement, and most of them the "standard" armature dimensions (See Table I).

The mechanical tolerances for closely wound CMF transducer coils are quite severe, as stated. Most units qualified only marginally; transducers with glaring deviations were eliminated.

A series of explosive expansions of varying armature designs (e.g., spun or drawn) and varying diameters were photographic-ly recorded. It turned out, that in spite of precision fit explosive, noticeable nonsymmetries in cone angle and boundary velocity existed. Worse, only armatures with diameters close to the standard design swept the coil turns with the wiping surface intact; armatures with lower diameters (promising higher Reynolds numbers) showed rippling and breakup before they had reached the last coil turn.

VII. ELECTRICAL MEASUREMENTS

A. Test Circuit

The test circuit is illustrated in Fig. 6. A capacitor C was discharged into the circuit by means of a vacuum or gas switch S. The armature was exploded in such a way that the crowbar contacts B were reached at the time where the current was close to its maximum. A current viewing resistor R and two current viewing transformers T measured the current I. The moment the generator coil was short-circuited, the two current viewing transformers saw different currents. The current difference, displayed on a sensitive scale, was used to determine the time of crowbar. A Rogowski coil determined $\dot{I}$, a differential voltmeter the voltage across the load. Measuring circuits had 100 MHz bandwidth. Care was taken to avoid ground loops.

The predictions of Eq. (10) for $R(t)$ and Eq. (13) for $L(t)$ were checked with a model, in which 11 different cone sections simulated progression of the armature down the coil. (Figure 5, top). Frequencies used were 100 kHz and 500 kHz. Excellent agreement for the initial 80% of the inductance function was obtained. The resistance measurements suffered from contact problems, but did not contradict the theoretical predictions.

B. General Comments

With non-ideal device tolerances, and with variations in the expansion behaviour of our armature, con-

FIG. 6: CIRCUIT USED FOR TESTING CMF GENERATORS

siderable scatter in the experimental data had to be expected. Other investigators using similar devices, had the same experience⁷.

Uneven closing of the armature leads to uneven contact speed and to uneven current rise, and the i graphs show a superimposed "clocking" frequency (See, e.g., Ref. 7). We found good correlation between the ratio of the amplitude of the clocking superposition to the mean i amplitude (clocking percentage), and the quality of the shot, measured by maximum current output.

Figure 7 shows an i curve with practically no clocking, and another measurement with high clocking. A current measurement is also shown. The current output of the second experiment was 40% less than that of the first. For evaluation, experiments which showed very low clocking were selected where available, i.e., we used the best shots rather than a statistical average.

Most experiments were conducted at very low injection currents to avoid high currents and voltages. The influences of heating and high voltage breakdown were thusly eliminated.

A look at Fig. 6 shows that there is compression of the field before crowbar occurs (we have a parametric circuit, the behavior of which is well understood). Our analysis, however, applies only after crowbar. For com-

FIG.7: ILLUSTRATION OF DATA RECORDS OBTAINED IN EXPERIMENTS. (A) TIME DERIVATIVE OF CURRENT FOR SEVERE CLOCKING AND (B) FOR LOW CLOCKING. (C) TIME-DEPENDENT OUTPUT CURRENT.

parison with devices which crowbar right at the beginning of armature expansion, a preamplification factor (which depends on the diameter of the armature, and is between 1.3 and 1.6) has to be added to our predictions.

C. Load Variations

A number of experiments were performed, where the generator (with standard armature) worked into loads between 100 and 2350 nHy: The expected theoretical maximum amplification ratio, and the expected time from half maximum to maximum current $(\Delta t)_{1/2}$ were determined. The results are shown in Fig. 8, with k chosen 1.2 and τ^* chosen 0.05, i.e., the insulation breakdown delay is 200 nanoseconds. Surprisingly good agreement with measurements was obtained.

D. Extended Last Turns

It has been observed previously, that the device showed improved performance, if the last few turns were wound at a higher pitch.⁹

There are a number of phenomena which influence the performance in this case. Decreased inductance, L_0 , increases the load ratio l for a given load. More flux is found between the turns, and the flux penetration factor k becomes larger. Compression is slower and skin depth is higher towards the end. These influences decrease performance.

FIG. 8: MAXIMUM CURRENT AMPLIFICATION, $I_{\max}/I_0$, AND CURRENT RISETIME FROM HALF MAXIMUM TO FULL MAXIMUM $(\Delta t)_{1/2}$ SHOWN AS A FUNCTION OF LOAD INDUCTANCE. SOLID CURVES ARE THEORETICAL CALCULATIONS.

On the other hand, the proximity factor f accounting for the turn-to-turn influence becomes considerably lower. Of particular importance is the reduction of the delay parameter τ^* , as the velocity of the contact along the armature is now sizeably reduced. For low inductance/resistance loads, these changes increase the amplification and generally outweigh negative factors. (Measurements are also somewhat more reproducible as the tolerances become relaxed at the end).

The theory presented is not directly suitable to calculate the resulting amplification. It can be used, however, to estimate the change in performance. For the standard coil, and a tripled pitch over the last three turns, a 20% improvement is predicted; 15 to 18% improvement is found experimentally.

E. Low Temperature Shots

Cooling the device to liquid nitrogen temperature will raise the magnetic Reynolds number from 1150 to 7650 for the standard armature model. The increase is almost solely due to the increase in conductivity σ . Lowering the temperature will, however, increase the hold-off capability of the insulator and therefore the delay parameter τ^* . The underlying physics is quite complex and not yet understood.

There are other phenomena which lower the gain which the increase in the Reynolds number promises (about

a factor of 2.4 according to Fig. 4). One of them stems from the fact that the load in our experiments was not cooled, and r was therefore relatively high. The real problem, however, is that cooling the device to N_2 temperature shrinks the explosive much more (by about 60 micrometer) than the armature, and all shots are imprecise due to a loose explosive. As expected, all experiments showed very high clocking.

With $r = .05$ and $\tau = .1$ (i.e., doubling the value of the breakdown parameter), the analysis predicts a total amplification of 110 vs. 74 at room temperature, i.e., a 48% improvement. Comparing experiments with similar clocking rate, a 30% improvement was found. With our lack of knowledge of insulator behaviour under shock, the discrepancy is not surprising.

F. Other Observations

A number of experiments at low currents were performed with the 25 micron insulating wrap removed, but with the wire insulation still present; it was somewhat damaged by wrap removal. Scaling linearly, the voltage hold-off capability of the insulation should now drop to one-half, as should the delay time constant τ^* . Analysis predicts a performance increase of about 33% both for room temperature and liquid N_2 temperature shots into 100 nHy loads. Again, comparing experiments with equal clocking rate, this improvement was found.

High current injection shots, not covered by our analysis, showed an expected deterioration of performance due to non-linear diffusion and insulation breakdown. At 950 amperes inspection current the amplification was only 57 (including preamplification), instead of 74 for a normal shot. At 54,000 amps, the field in the coil at the last moment of compression was 1.4 megagauss.

VIII. CONCLUSION

We have presented a linear theory of closely wound helical CMF devices. It was attempted to take all physical phenomena into account which apply at low currents and low voltages. In spite of the omission of heating, non-linear diffusion, and electrical breakdown, the theoretical treatment turned out to be quite involved. It became necessary to carry two adjustable parameters. One of them, the flux penetration factor k , varies very little for normal designs. Another one, the breakdown delay time t^* of an insulator under shockwave impingement, is less well known, especially at very low temperatures. Grace is saved by the fact that for reasonably high inductive loads ($\geq 2 \times 10^{-3}$ of the initial coil inductance), the effect of variations in the adjustable parameters is small. The analysis uses a systems description with 10 measurable quantities (plus time) and is therefore very broad. The essential result beyond elementary theory is that the performance of closely wound helical CMF devices is largely

determined by flux left in the coil/armature at the end of mechanical compression; considerable load dependence of output current and end rise time is predicted.

The experiments were fraught with mechanical problems, which led to considerable scatter of the electrical data. "Good" experiments could be recognized by the smooth behaviour of the current derivative and only such were made the basis for evaluation. Fortunately, a large number of devices were available.

The theory predicts output and rise time well for load variations at room temperature. It furnishes a reasonable semi-quantitative explanation for coils with extended last turns. Attempts to vary the magnetic Reynolds number by decreasing the diameter of the armature failed due to early armature breakup. A sizeable change in Reynolds number was effected by cooling the CMF device to liquid nitrogen temperature; the resulting improvement is compatible with predictions. A number of high current experiments, (not covered by the analysis), were performed - expectedly, a fall-off in amplification is observed when the critical field strength is exceeded.

The work described furnishes a number of guidelines for improving CMF multiplier designs: For reproducibility of output, the mechanical tolerances have to be narrowed. Armature design has to be improved - some sacrifice in compression velocity may have to be accepted. The design has to be tailored to the load. The insulating material has to be replaced by

one with high voltage hold-off capability under normal conditions, but rapid breakdown under mechanical shock. With this, we will have a useful device with many applications. :

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