IMPROVEMENTS IN RANCHERO MAGNETIC FLUX COMPRESSION GENERATORS *

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Abstract

Los Alamos "Ranchero" Magnetic Flux Compression Generators (FCGs) have been used to power imploding liner loads. The fundamental FCG design is based on a cylindrical detonation system that expands the armature simultaneously into a coaxial generator volume and has been shown to generate currents as high as 76 MA. Analysis of the 76 MA test results revealed a weakness in the design at the output glide plane. To prevent premature shorting at the output current slot of the generator, the armature/glide plane interface was originally designed to lag the leading edge of the armature. However, 2D-MHD calculations reveal that at very high currents a magnetically driven aneurism develops in this lagging section which reduces the performance of the generator. A new model Ranchero is being developed to correct this weakness and provide enhanced performance. In the new model, the output glide plane is eliminated and the armature is extended along the FCG axis, with its radius increasing along a curve until it reaches the current output slot. A cylindrical detonation system of the type required for earlier designs continues to be used, and the high explosive (HE) in the extended section is detonated by the last point of the cylindrical detonator. The stator of the FCG is contoured, allowing the contact point of the armature to zipper from the input to the output end in the last few µs of flux compression. In addition, the new model Ranchero is intended to use PBX 9501 (9501) for the HE and also remove the smoothing layer, which has been part of all Ranchero HE systems to date. Both of these factors lead to increased performance. 9501 is more energetic than the PBXN 110 used in Ranchero generators to date, and both calculations and experiments have shown that the smoothing layer is not needed when the detonator point spacing is 18 mm. Tests of original model Rancheros using PBXN 110 castable HE, with an imbedded smoothing layer, demonstrated an armature expansion velocity of 3.1 mm/µs. Further tests show that removal of the smoothing layer increases the speed to 3.3 mm/µs, and replacement of the cast PBXN 110 with 9501 without a smoother gives a velocity of 3.8 mm/µs. Designs, concerns, and experimental results facilitating the new model Ranchero are presented. In addition, performance estimates are given for the initial imploding liner tests to be conducted, and further computational details are presented in a companion paper given by C. L. Rousculp and others at this conference.

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I. INTRODUCTION

Los Alamos has conducted experiments with Ranchero FCGs since 1996, and several pulsed power and load configurations have been explored [1]. The generator HE is detonated by a linear array of slapper detonators on-axis. These detonators are manufactured in lengths of 43 cm, 76 cm, 100 cm, and 144 cm with 18 mm between slappers. The baseline configuration for 43 cm Ranchero devices with a simple liner load is given in Fig. 1. The 43 cm module has a taper of 3 mm over the 43 cm length on

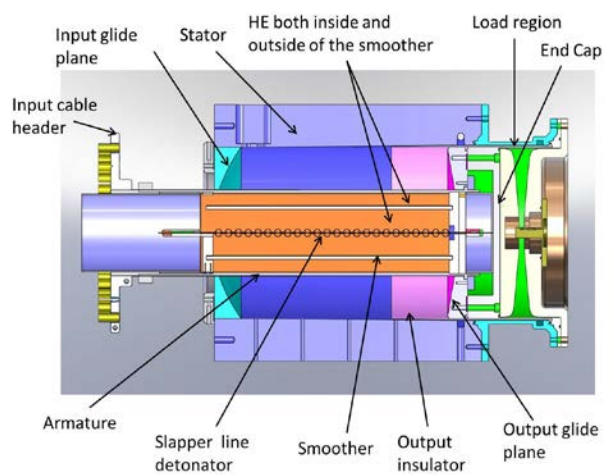

Figure 1. Baseline Ranchero configuration with 43 cm detonation system and an imploding liner load. For the minimum inductance load, the stator is connected to the output glide plane with a plate contoured to match the current joints shown here.

the stator, and all longer modules have a slope of 3 mm per 50 cm. With a very low inductance load in place of the liner shown in the figure, and 3.76 MA initial current, the generator in Fig. 1 has produced a 76 MA peak current pulse.

This was an encouraging result, but post-experiment modeling of the as-built experiment revealed a weakness in the design. Fig. 2 illustrates the issue. The armature/ glide plane interface is carefully designed to lag the armature and thereby prevent premature closure of the generator output section. This interface has a higher linear current density (current per azimuthal cm) than the rest of the system, and at the 76 MA level modeling shows that an aneurism develops in this high pressure region. This aneurism is further exacerbated by a manufacturing feature. Careful modeling has revealed that a chamfer for installing the slapper detonator centering fixtures left a small void in the aluminum which seeded the problem. However, the aneurism still occurred at a similar level in computations in which the void was removed. With a very small load inductance, the aneurism inductance and resistance played a major role in limiting the current to 76 MA. Comparing experimental results to earlier Ranchero data at 45 MA (reference 1 Table 2, Row C) indicates that the aneurism adds as much as 1 nH to the circuit.

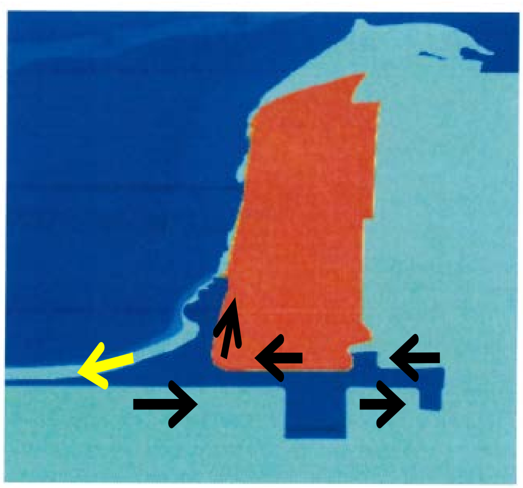

Figure 2. Result from an MHD simulation of the Ranchero experiment which had a peak current of 76 MA. The red is the output glide plane, the light blue regions are FCG conductors, the upper dark blue region is the detonation by-products, and the lower dark blue area has SF_6 in the collapsing void and load. Current flows along the surfaces enclosing the collapsing void and load as shown by the arrows. The curved conductor at the glide plane is the armature, and the aneurism is seen where the armature adjoins the glide plane. This aneurism adds parasitic inductance to the system, and the very thin armature section adds resistance and will ultimately fuse.

A second limiting condition in the baseline Ranchero configuration is the HE pressure and kinetic energy in the armature. The 43cm long, 6 mm thick Al armature, propelled by PBXN 110, expands at about 3.1 mm/μs, and has kinetic energy of about 16 MJ. During the armature expansion, HE products exhaust axially, and the remnant HE gas pressure behind the expanding armature has dropped to much less than 10 kbar by peak current. At this time, the magnetic pressure is ~50 kbar. The energy in the magnetic field at the end of the experiment (including any lost through Ohmic heating) has increased from 0.4 MJ to about 8 MJ which considerably retards the armature. Although this is good efficiency, for substantial load inductances the effect will be greater because the initial current must be higher to achieve the same final current. The significance is that for high current experiments, a large fraction of initial kinetic energy will be extracted from the armature, and there is no additional energy available from the explosives products.

II. ENHANCED RANCHERO DESIGN

To address the issues discussed above, an enhanced Ranchero design is being developed. Fig. 3 illustrates the new design. A Ranchero "S" generator is initiated in a cylindrical section by a slapper system of the desired length. The one in the figure is 43 cm long. An extra section of HE is added to the end of the cylindrical charge, and the detonation proceeds from the end of the slapper system along the "swoop" in a way that drives the armature into the stator almost simultaneously, but with enough taper to zipper from the input to the output in the final microseconds. The calculated inductance (L) and dL/dt curves are given in Fig. 4.

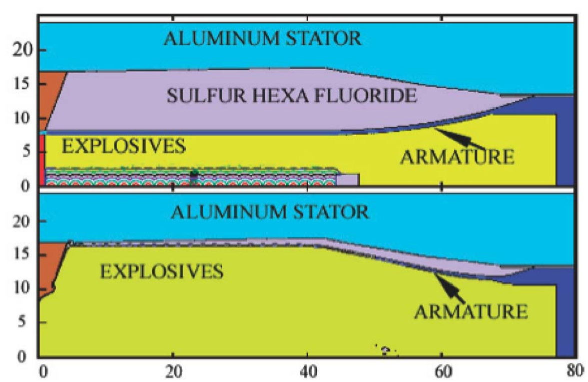

Figure 3. 2-D Hydrodynamic calculation of Ranchero S concept. There is no output glide plane in this design, and the armature is supported by full detonation pressure near the output. The first frame (t=0) shows the initial contours and slapper initiation points, and the second frame (t=34.5μs) shows the contours as the armature approaches the stator. First armature motion is ~10 μs. Inductance at first motion is ~86 nH, and at frame two is ~9 nH.

2D-MHD calculations have been performed with a finalized design, and indications are that the new design principles will operate as expected. The detonation front has just passed the output slot at final closure time, and has expanded very little. In addition, using an FCG such as Fig. 3, but with a 100 cm coax section in place of the 43 cm coax shown, calculations indicate that a current of 85 MA can be delivered to a 10 nH initial-inductance static load given an initial current of 12 MA. A seed current of this size can be easily generated using a helical booster generator. The circumference of the output of this module is 85 cm, and thus we expect to be able to use it at a level of 1 MA/cm. FCGs can operate at higher linear current densities, but losses increase dramatically and this is our nominal design limit.

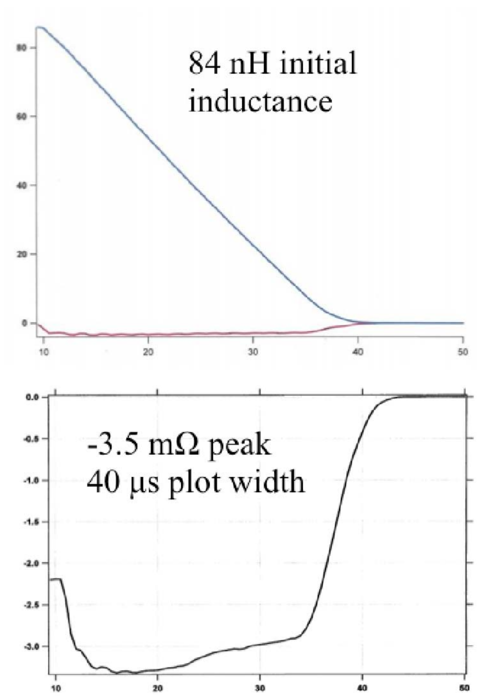

Figure 4. L and dL/dt for the FCG in Fig. 3. Operation time is from ~10 μs to ~40 μs.

III. MANUFACTURING CONSIDERATIONS

A family of Ranchero FCGs that arises naturally from this concept is illustrated in Fig. 5. The Ranchero S family is intended to use PBX 9501 (9501) high explosive. This is a higher performance HE than the PBXN 110 that has been used to date. To use this HE, some issues must be addressed, and small scale tests have been performed accordingly. 9501 has a much more abrupt shock profile than the previously used PBXN 110, and one concern was that the 6 mm thick annealed armature would be destroyed by the profile and not remain suitable for flux compression. A subsystem test was conducted which demonstrated that the armature would survive and achieve an expansion velocity of 3.8 mm/μs, as compared to 3.1 mm/μs in tests to date, with PBXN 110 and the smoother shown in Fig. 1. Fig. 6 shows the good condition of the armature at 2X expansion on that test.

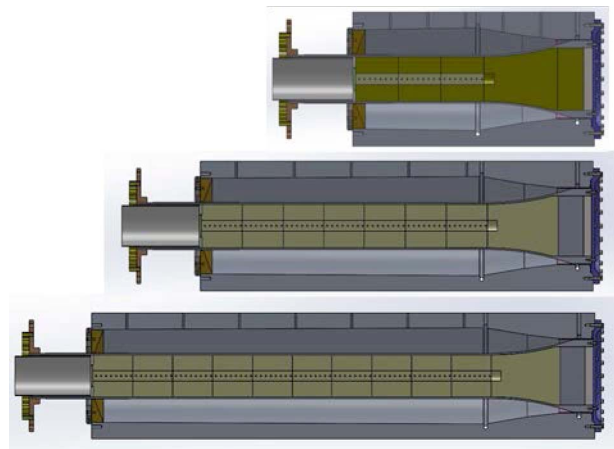

Figure 5. Family of Ranchero S generators using 43 cm, 100 cm, or 144 cm detonation systems. Initial inductances are approximately 86 nH, 170 nH, and 225 nH respectively.

Figure 6. Framing camera record of armature expansion driven by 19.4 cm long 9501 initiated on 18 mm centers at the midplane of the HE cylinder. The 167 mm diameter, 6 mm thick annealed Al armature has expanded by a factor of two in this frame, and it is in good condition for flux compression.

To fabricate the HE charges necessary for these generators with machined HE, individual 9501 charges must be fabricated and glued together. This gives rise to the concern that the glue joints will cause the armatures to be cut along the joints, and trap flux or fail to compress it. Another series of small scale tests has shown that glue joints with a thickness of 50 µm will satisfactorily expand a 6 mm thick 6061-T0 Al armature, but in a region where compound joints with an effectively larger glue joint occurs, a rupture has been observed.

Fig. 7 shows the HE assembly used in the test. The glue joints in the assembly routinely measured about 50 µm thick, but a machining error on one of the half-cylinders left a gap of 125 µm plus the nominal glue thickness. This joint was purposely put in the field of the view to the framing camera, and it is seen to rupture at the location of the compound joint.

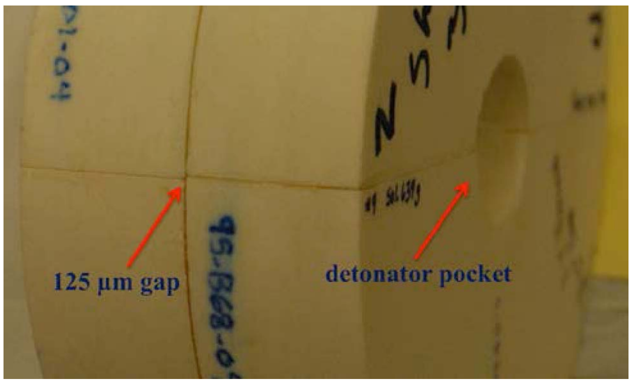

Figure 7. Armature charge with two 30 mm long 9501 half-cylinders glued together to create cylinders, and two of these glued together to make a 60 mm long cylinder. The detonator pockets were bored to different depths so that the middle of the 18 mm detonator spacing was offset by 3 mm from the glue joint. All glue joints were ~50 µm thick, but a machining error left an extra gap of 125 µm at this compound joint, and it is seen to rupture in the dynamic record.

Three dynamic frames are presented in Fig. 8. Unfortunately the compound joint having no machining flaw was occluded in the mirror image before 2X expansion was reached, and there is no data on that joint from this test. The location of all glue joints can be detected in the middle frame, but the only rupture is at the machining flaw. Further work is underway to assure the HE fabrication yields no unacceptable gaps, and at least one satisfactory option exists. The final fabrication issue is inserting the armature HE into the armature tube. For these designs, the HE must be assembled separately and then installed into the armature. Past practices have included cooling the HE to gain extra clearance during assembly, and this remains a possibility. However, in the test shown in Fig. 5, there are gaps as large as 250 µm between the HE and the armature assembly and no problem is observed. To save manufacturing costs, the initial design will allow such gaps, and shim the charge to center for the best precision fit once assembled.

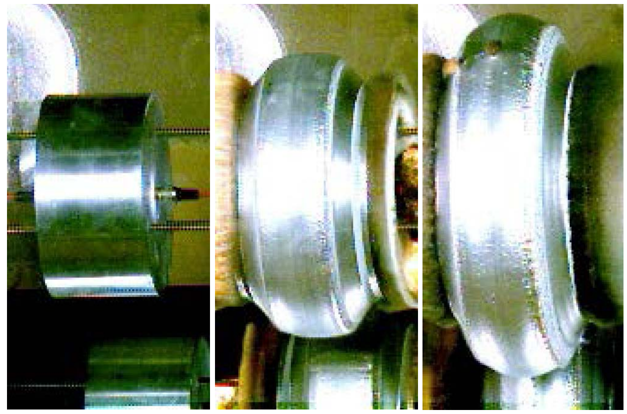

Figure 8. One static and two dynamic images of an expanding 6 mm thick 167 mm diameter Al armature driven by the charge in Fig. 6. The armature is initially 94 mm long, and there are polycarbonate spacers 17 mm long to hold the HE in place and locate the detonators. Evidence of all glue joints is seen in the middle frame, but the only rupture is in the upper compound joint where a machining flaw created a 125µm gap. The compound joint with no flaw, seen in the mirror view, is occluded in the last frame, and no data was obtained at this degree of expansion.

IV. IMPLODING LINER TEST

Initial experiments using the Ranchero-S system will implode solid liner loads. Although the optimal liner initial diameter is larger, available material dictates that the initial liner radius equal 8 cm. With this constraint, a set of screening calculations has been performed, and liners between 2 and 6 mm are seen to implode intact to a radius of 1 cm. In the calculation for 2 mm thick liners, an implosion velocity of 13 mm/µs was seen, and at 6 mm thickness, the liner velocity was 8.8 mm/µs. A liner 1 mm thick melted and did not implode intact. The first test will use a somewhat conservative 5 mm thick liner which reaches 10.4 mm/µs in the calculation, and does not greatly increase the inductance by peak current. Peak current is predicted to be 44 MA, given an initial current of 3.75 MA, and the waveform is given in Fig. 9.

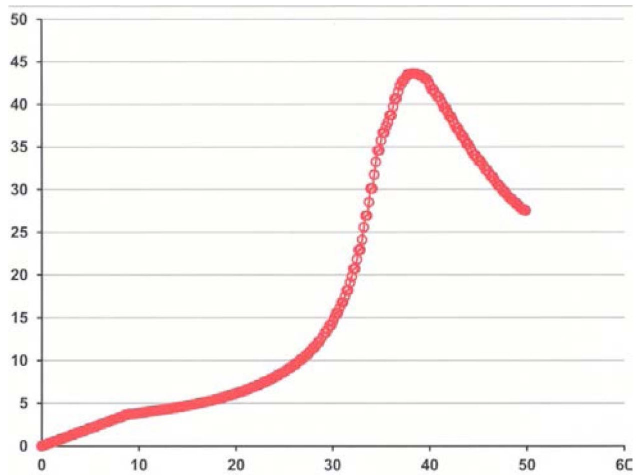

Figure 9. Current computed for 5 mm thick liner experiment. Seed current is provided by a 9.3 µs ramp to 3.75 MA in this calculation.

V. SUMMARY

The family of Ranchero Generators has been expanded to include a new design that eliminates glide planes at the output of the FCG, and supports the armature with full HE pressure at final closure time. The new version corrects for a weakness in the original design that affects very high current performance, and which was experienced in a test at 76 MA peak current. The decision to use PBX 9501 explosive provides a higher performance armature, but has mandated some small scale experimental work to assure that the armature will survive intact during flux compression. The first 43-S experiment will attempt to implode a 5 mm thick, 8 cm radius solid Al liner to velocity of ~10 mm/µs at 1 cm radius. The initial load inductance is ~2.5 nH, and has increased by final flux compression time to about 5 nH. With 3.75 MA initial current, a peak current of 44 MA will be generated as shown in Fig. 8, and calculations show that a heavier (6 mm thick) liner would move less, allowing a peak current of 47 MA but decreasing the peak liner velocity to ~9 mm/µs.

VI. REFERENCES

[1] J. H. Goforth and others, "Ranchero Status Report 2012," Los Alamos National Laboratory internal report LA-144
63, July 2013.