LA-UR-16-26685
Approved for public release; distribution is unlimited.

Title: The search for a 100MA RancheroS magnetic flux compression generator

Author(s): Watt, Robert Gregory

Intended for: Report

Issued: 2016-09-01

The search for a 100MA RancheroS magnetic flux compression generator

R. G. Watt 160829

Abstract

The Eulerian AMR rad-hydro-MHD code Roxane (Appendix A) was used to investigate modifications to existing designs of the new RancheroS class of Magnetic Flux Compression Generators (FCGs) which might allow some members of this FCG family to exceed 100 MA driving a 10 nH *static* load. This report details the results of that study and proposes a specific generator modification which seems to satisfy both the peak current and desired risetime for the current pulse into the load. The details of the study and necessary modifications will presented. For details of the LA43S RancheroS FCG design and predictions for the first use of the generator refer to Reference 1.

Introduction

A need has arisen to determine what changes might to be made to the *as designed* LA43S, LA72S, LA100S, and LA144S magnetic flux compression generators to allow them to produce of order 100 MA into a 10 nH *static* load. For reference a comparison of the original Ranchero and the new RancheroS generators, driving a low inductance load, is shown in Figure 1. The *as built* LA43S with an 8.22 cm initial armature outer radius and a 13.2 cm power flow channel driving a *static* 10 nH load only attains about 65 MA from a 12 MA seed current according to Roxane simulations. The peak current attainable is limited for this 43 cm straight section FCG by the *effective* gain of the generator ($L_{system}(0)/(L_{load}(t_{peak}) + L_{soak}(t_{peak}) + L_{gap}(t_{peak}))$ which is of order 5.5, despite an *ideal* gain of 9.7 for the system without diffusion and assuming complete gap closure. This *effective* gain combines the magnetic flux lost to diffusion into the aluminum, resistive losses, and any residual unclosed gap between the armature and the stator. At the 65 MA current peak level, little residual gap is seen in simulations, but this is not the case for the larger generators and higher peak currents.

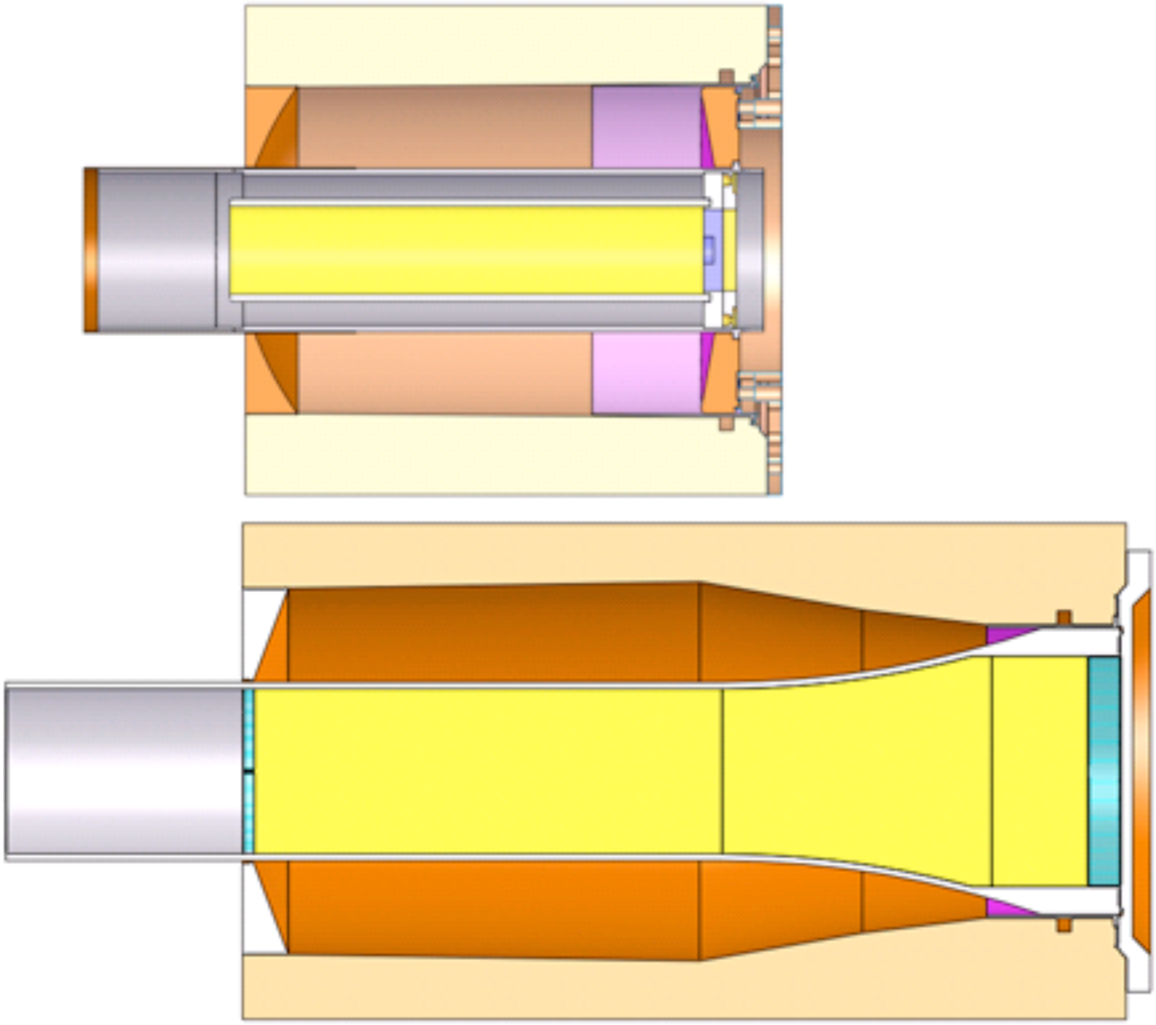

Figure 1. A comparison of the original 43 cm Ranchero (top) and new 43 cm RancheroS (bottom, *as built* for a shot in FY17). The low inductance load in each case is simply a Faraday Rotation current measurement groove with ~ 0.5 nH inductance.

Other, bigger members of the RancheroS family appear to be clamped to around 80-85 MA due to excessive magnetic pressure[2], using the same 12 MA seed current with the 10 nH load. *(Pmag scales with $(I/R)^2$)*. Figure 2 shows the baseline systems driving a 10 nH load and demonstrates the apparent clamping near 80 MA.

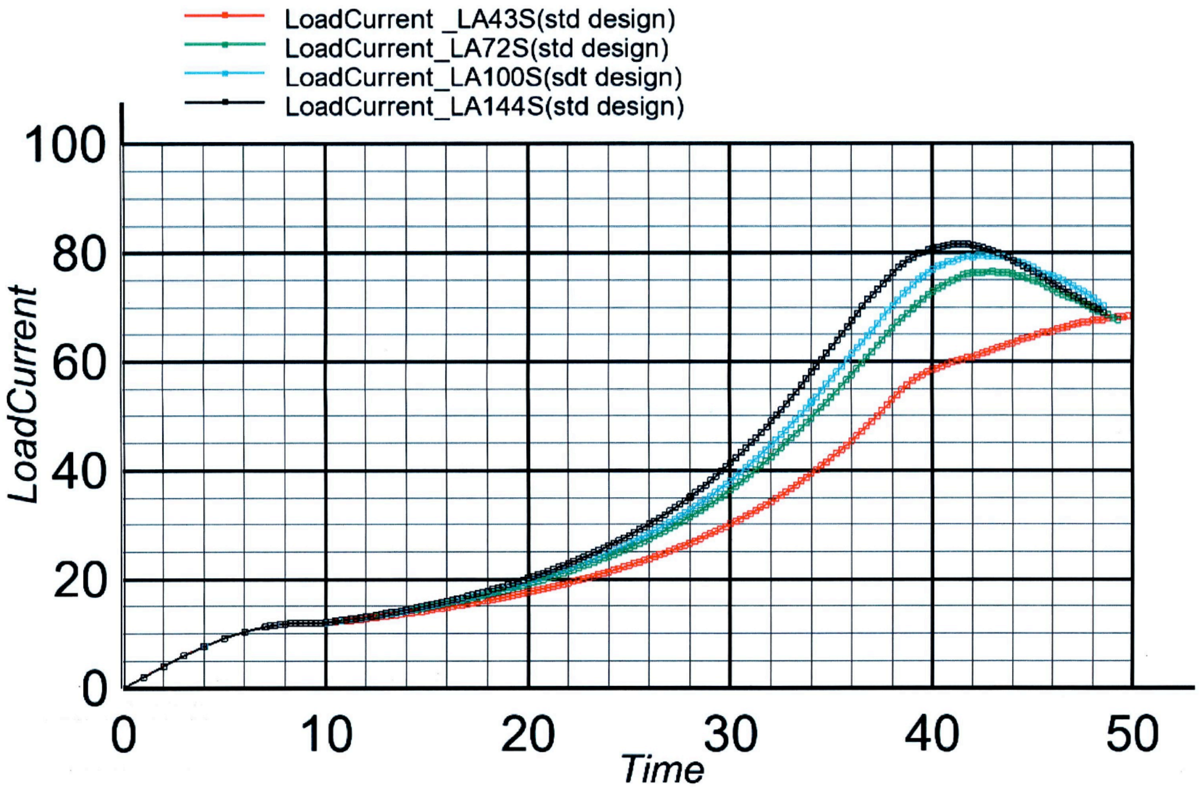

Figure 2. The four existing RancheroS generator designs driving a 10 nH *static* load appear to clamp at around 80 MA due to magnetic pressure stopping the armature prior to complete collapse of the SF6 filled void in the FCG body.

Because the larger generators seem unable to drive 100 MA currents due to an apparent magnetic pressure limit, a study was made of the effect of photographic enlargement of all dimensions of the LA43S FCG driving a 10 nH load[3], as was done in the case of the LLNL miniG/934 FCG set. This enlargement was expected to increase the current at which the magnetic pressure began to clamp the peak current attained because all conductors were now a larger radius. The pure photographic enlargement (equal axial and radial expansion) worked well. A purely photographic enlargement by 1.375x exceeded 100 MA at 12 MA seed, with a current waveform that resembled that simulated for the *as built* LA43S waveform, albeit with a longer risetime due the increased total system inductance. Pure photographic expansion of the geometry, which holds $\log(R_s/R_a)$ fixed at the original values over each small section of the entire system, including the load cavity, also leads to an increase in all lengths so that the load inductance actually increased with the expansion as did the inductance of the generator in these simulations. The 1.375x FCG ultimately drove more than the desired 10 nH load in these simulations. This was a result of the simulation setup used here and not inherent in the photographic enlargement technique. The result of a photographic expansion of the generator only, with a *constant* 10 nH load inductance, would be a somewhat higher peak current than that shown in Figure 3, which shows the results of this study. The increase in all lengths is what leads to the longer rise times seen in Figure 3.

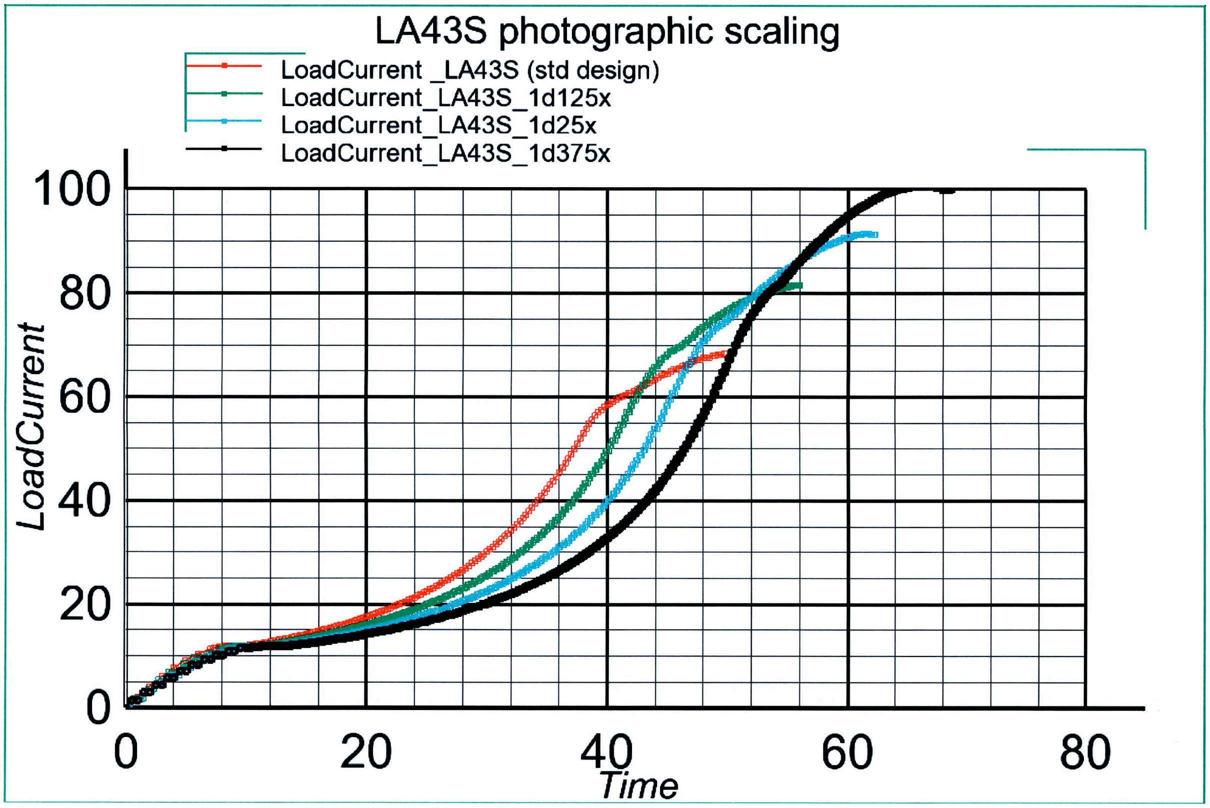

Figure 3. The response of a *full system* photographic enlargement of the LA43S generator into a load inductance which increases from 10 nH to 13.75 nH upon a 1.375x enlargement. While the current level exceeds 100 MA with 12 MA seed, it does so at the expense of a longer risetime.

Constant risetime generator results

Because the longer risetime of a purely photographic enlargement is not desirable, further variations of the systems as a whole were studied[4]. To retain the ~ 25 us risetime of the LA43S FCG and sister generators while getting past the seemingly inherent 80 MA limit imposed by the magnetic pressure acting on the armature, given an armature outer radius of 8.22 cm and a PFC inner radius of 13.2 cm, it is necessary to increase the armature radius so the same limiting magnetic pressure occurs at a higher delivered peak current. To avoid the rise time increase of a purely photographic enlargement, it is necessary to hold the armature-stator gap fixed as the radius is increased. It is also desirable to keep the armature thickness fixed to retain the final armature velocity of the smaller radius FCG. If the armature inner and outer radii are increased by equal amounts, holding the armature-stator gap fixed, without changing the length of any components, and holding the load fixed at 10 nH, the attained current increases as expected as the magnetic pressure becomes less dominant. Figure 4 shows a CAD model comparison between a normal LA43S armature/stator configuration and the same profiles shifted to a larger armature outer radius by 2 cm. The two images are the same scale. The lengths are the same but the components are larger by 2 cm in radius in the model on the right.

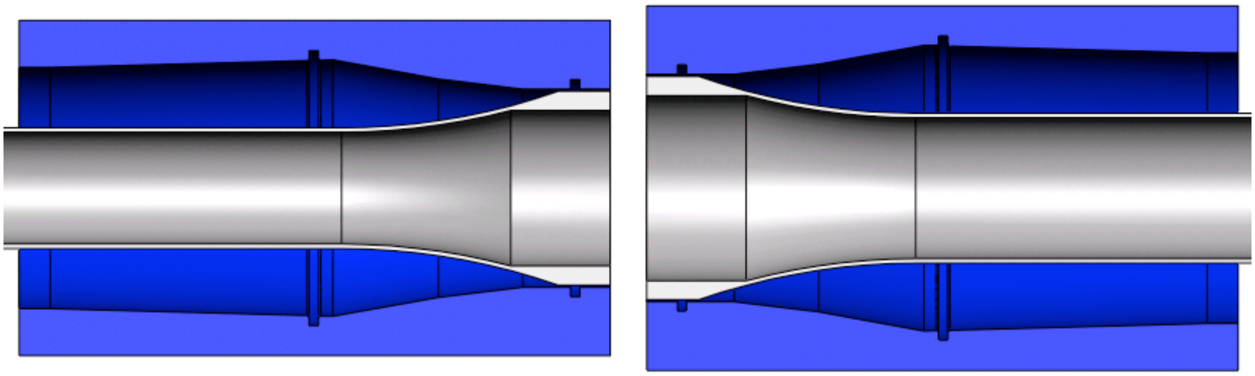

Figure 4. The *as designed* LA43S generator showing the armature and stator (left) to be used in the first experiment with the RancheroS in FY17 and the same generator with its profiles retained but increased in radius by 2 cm, which should allow approximately 25% higher current before clamping due to magnetic pressure.

The LA43S system response is shown in Figure 5, where the current waveforms are shown for three different armature radii (R_a=R_o, R_o+2cm, and R_o+4cm). Because the generator inductance fell from 87 nH in the standard LA43S to 74% of that value with a 4 cm radius increase, the *ideal* gain dropped from an acceptable but energy starved 9.7 to about 7.5. The radially larger LA43S system thus can only attain about 85-90 MA even if the ideal gain is attained, with a 12 MA seed, despite the bigger diameter. Since the *effective* gain is even lower due to diffusion losses into the metal, residual open gap, and resistive energy losses, while the peak current was higher than the 65 MA of the *as designed* LA43S, and it clearly showed signs of improved performance at larger radius, it never exceeded 80 MA.

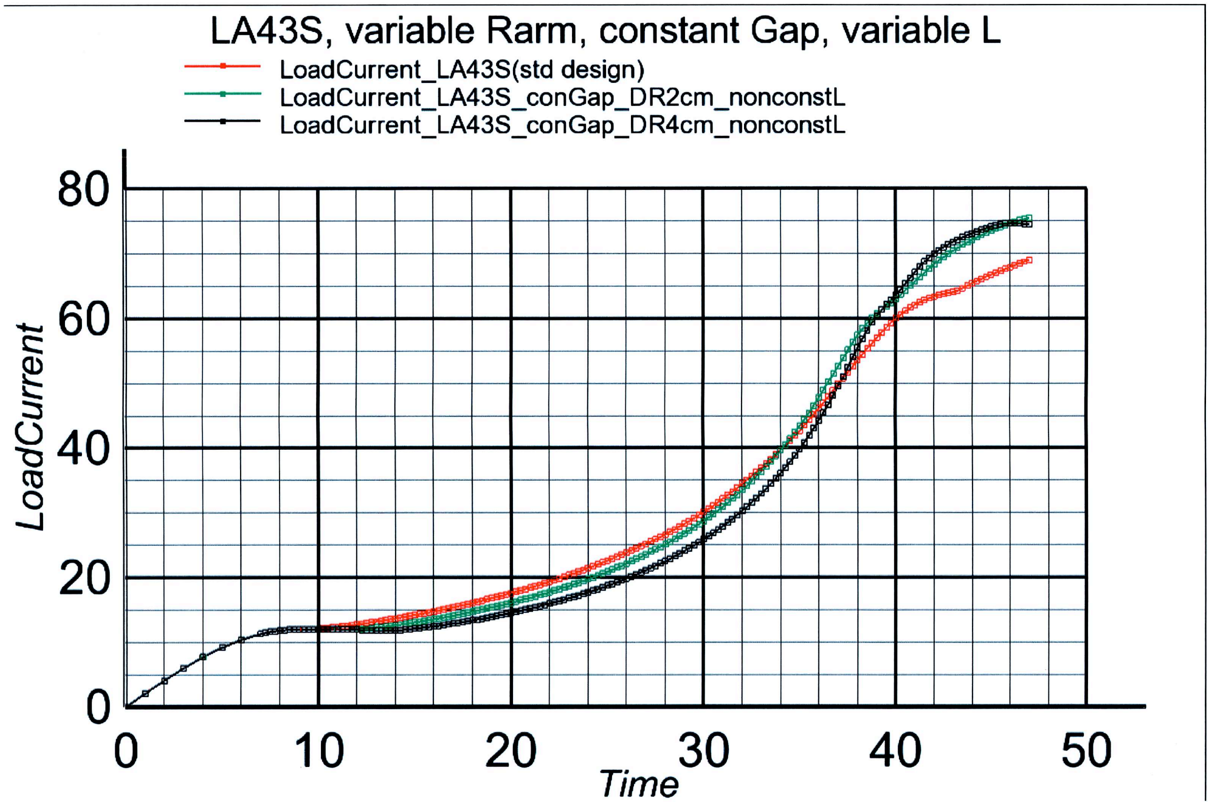

Figure 5. An LA43S system driving a 10 nH cavity. The system inductance drops with increasing radius due to $\log(R_s/R_a)$ without any compensating increase in FCG overall length. As desired the temporal history remains the same with the attained peak current increasing as the generator came out of the magnetic pressure dominated regime. The small LA43S generator ran out of gain before 100 MA was attained.

As of result of the inability of the standard 43 cm RancheroS to reach 100 MA at larger radius, the bigger generators were examined. Recall that the *ideal* gain $G = ((L_{FCG} + L_{load}) / L_{load})$. Also recall $L_{FCG\_straight\_section} = 2(nH/cm) * Z(cm) * \log((R_{so} + \delta)/(R_{ao} + \delta))$ where R_{so} and R_{ao} are the 16.44 cm and 8.22 cm of the standard design, and δ is the additional radius. Since the inductance/length drops as R_s/R_a drops at larger radius, the system inductance drops as R_a is increased, reducing the *ideal* gain. In an effort to not lose the *ideal* gain, an extra length was added to the straight section of each generator design such that the initial inductance loss due to the decrease in $\log((R_{so} + \delta)/(R_{ao} + \delta))$ was just compensated for by added length in the straight section. This insures that the *ideal* gain did not change as the radius was increased. This is the simplest way to insure that the generator should be able to perform in a near *ideal* manner. Nearly 100 MA was achieved with the two largest generators in this study as shown in Figure 6, when the armature was increased by 2 cm for all four variants.

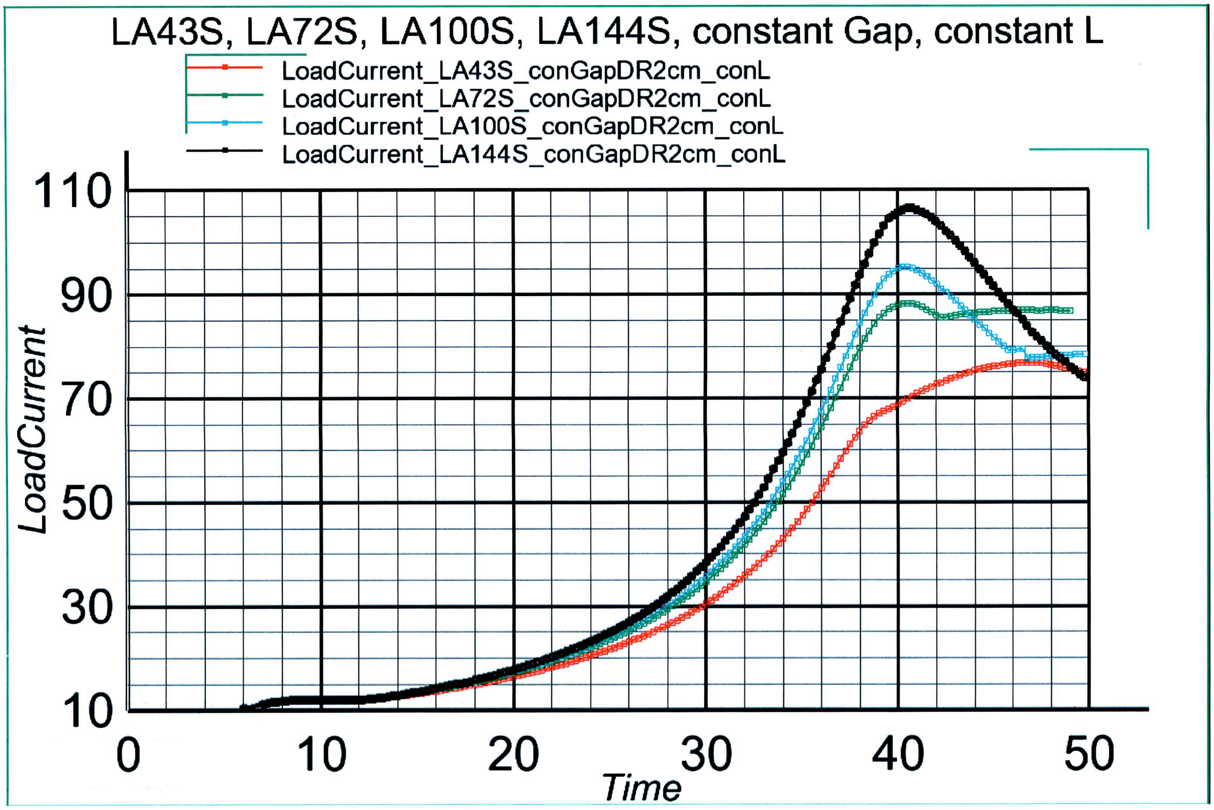

Figure 6. The RancheroS family of generators, with an extra 2 cm radius and enough added length in the straight section to compensate for the reduction in log(R_s/R_a) at larger R_a. This holds L_{FCG} and L_{load} fixed. This then holds the *ideal* gain fixed while the radius is increased, while removing the magnetic pressure clamp on the peak current originally dominant for the larger generators. The armature profile is identical to the LA43S profile with all the armature length addition in the straight section, with an increased OR of 10.22 cm. The overall straight section lengths are not constrained to match available detonator circuits.

While this *best of all worlds* approach clearly works as expected at any larger radius, it has the disadvantage that it adds to the overall length of the detonator required and would require both new detonator assembly development and a significant increase in the HE load beyond that required by the radius increase alone. The LA144S FCG with both larger radius and increased length looked so promising in this series that the standard LA144S FCG was studied as a function of radius increase but without the new length added. This, then, would *not* require new development except for the larger diameter HE charge. As it turned out, the almost 50 cm additional length used in Figure 6 was not really needed in order to reach 100 MA. The behavior of the LA144S FCG at large radius was studied in detail for a set of radial increases between 0.5 cm and 4 cm. Figure 7 shows a suite of current histories using the baseline LA144S detonator assembly and standard HE charge lengths, driving a 10 nH *static* load with various radial increases in all the profiles. As can be seen, any radial increase of 1.5 cm or more will allow the FCG to reach the 100 MA range with a 10 nH *static* load.

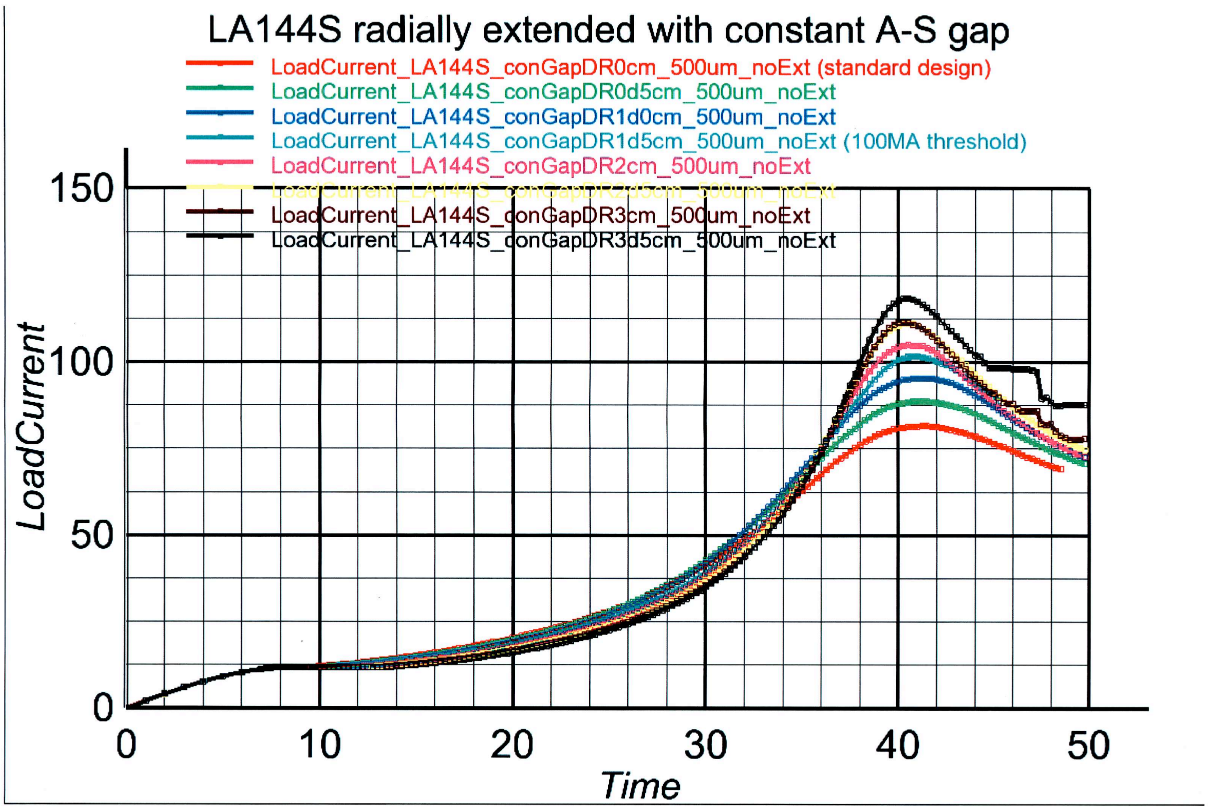

Figure 7. LA144S with increased armature and stator radius, using all the standard design components simply increased in radius, achieves the desired 100 MA with similar rise time to the baseline system, driving a *static* 10nH load. The threshold radius increase required is about 1.5 cm. Anything larger than this should reach the desired maximum current with headroom for losses not present in the simulation, if any.

A prescription for *new* generator design

A prescription for a *new* generator able to attain 120 MA with a 12 MA seed into a 10 nH load would start with an FCG design having inductance large enough that the *ideal* gain $G = ((L_{FCG} + L_{load}) / L_{load}) >> 10$. If that generator had the standard 8.22 cm armature OR and the LA43S armature profile with PFC IR of 13.2 cm like LA43S, Figure 1 suggests that it will clamp at 80 MA. An example of such a generator would be LA144S, whose initial inductance is around 230 nH of which 200 nH is in the straight section and an additional 30 nH is in the bell. With an *ideal* gain of 24 into 10 nH, it should run up to the clamp pressure and stop evolving. Then the generator would be increased in armature radius at fixed armature thickness and armature-stator gap to attain the same pressure clamp value at 120 MA and some new radius as occurred at 80 MA at the original radius. This would require an armature outer radius in the straight section of 12.3 cm if only $(I/R)^2$ were in control. That would correspond to a δ of 4 cm which was looked at and did reach about 118 MA, when the additional 50 cm or so was added to retain the baseline 230 nH inductance at the larger radius. That large an increase in both radius and length would require an increase of more than 50% in the HE charge and may be excessive, since the basic assumption was that the radius should scale up by 1.5 to reach a maximum current of 1.5 times the original current clamp at 80 MA.

A reasonable solution

Figure 7 suggests the better answer is to accept the FCG inductance reduction due to $\log(R_s/R_a)$ at larger R_a and simply increase the radius R_a somewhat past that needed according to simulations, counting on the additional headroom to take care of any undetermined losses. This constrains the new design to use existing slapper assemblies and determines the minimum additional radius δ that needs to be added in order for I_{max} to exceed 100 MA at a given seed current. From Figure 7, a 1.5 cm radial increase should reach the 100 MA level with a 12 MA seed. To allow for headroom, it would be wise to choose a 2 cm increase instead, which should exceed 100 MA for that seed current. For a generator in which the 144 cm detonator assembly is used, with an HE charge of 9.62 cm radius, armature 6 mm thick with the LA43S armature inner profile moved to the new 9.62 cm inner radius in the straight section, the FCG inductance should be approximately 200 nH, of which about 170 nH is in the straight section and around 30 nH is in the bell section. The *ideal* gain into 10 nH is 21, producing a simulated *effective* gain at 105 MA peak current of 8.75x. The reduction in the gain from the *ideal* is composed of more than 6 nH residual inductance in the FCG body due to an unclosed gap and an increase to 11.2 nH in the load cavity due to distortion at high current. The resulting 17.2 nH identified in the SF6 cavities at peak current would have produced about 150 MA in the absence of diffusion and resistive losses, so the observed 105 MA still has additional losses. Roxane reported an additional 14 nH on the calculational mesh which accounts for the diffusion into the metal, but not all of that is actually lost or the peak current would not even reach the 105 MA seen Figure 7. (It appears that the 14 nH reported as extra on the mesh, which is the magnetic flux in the metal, effectively represents about 6-7 nH of residual inductance in an *effective* gain calculation.) Not much can be done to reduce the losses which are determined by the resistivity of the aluminum which controls both the penetration depth and the local heating of the metal.

An experimental result into 10 nH should look like the magenta (5th) curve in Figure 7. Note that the 10 nH cavity deforms at this current level adding more than 1 nH to the initial 10 nH cavity, and the bell gap still does not close completely. Note also that the normal crowbar between the straight section and the bell seen in the LA43S generator at all current levels up to around 80 MA is not present in the Roxane simulation for the LA144S generator set. The desire to crowbar the straight section so magnetic flux can not be pulled back out of the load after peak current may require further refinement of the placement and corner structure of the FR groove in the middle of the FCG body. That should be examined further if any of the larger generators are invoked for high current experiments. There remains a very real question of whether in a real system crowbarring might always occur locally when the local armature-stator gap closes momentarily, in which case the curves in Figure 7 would under-estimate the attained peak current. In the absence of a validated shorting model in Roxane, crowbarring of the FCG from the load remains problematic in the simulations.

For future discussions, it is useful to have a plot of ideal gain vs. additional radius for the various RancheroS designs. Figure 8 is such a plot, and also shows the effective (realized) gain approach to the ideal gain for the 144 cm generators in Figure 7, as reported by Roxane, for future reference. As can be seen in this figure, the effective gain is at most about 50% of the ideal gain, a reasonable figure of merit for design discussions in the future.

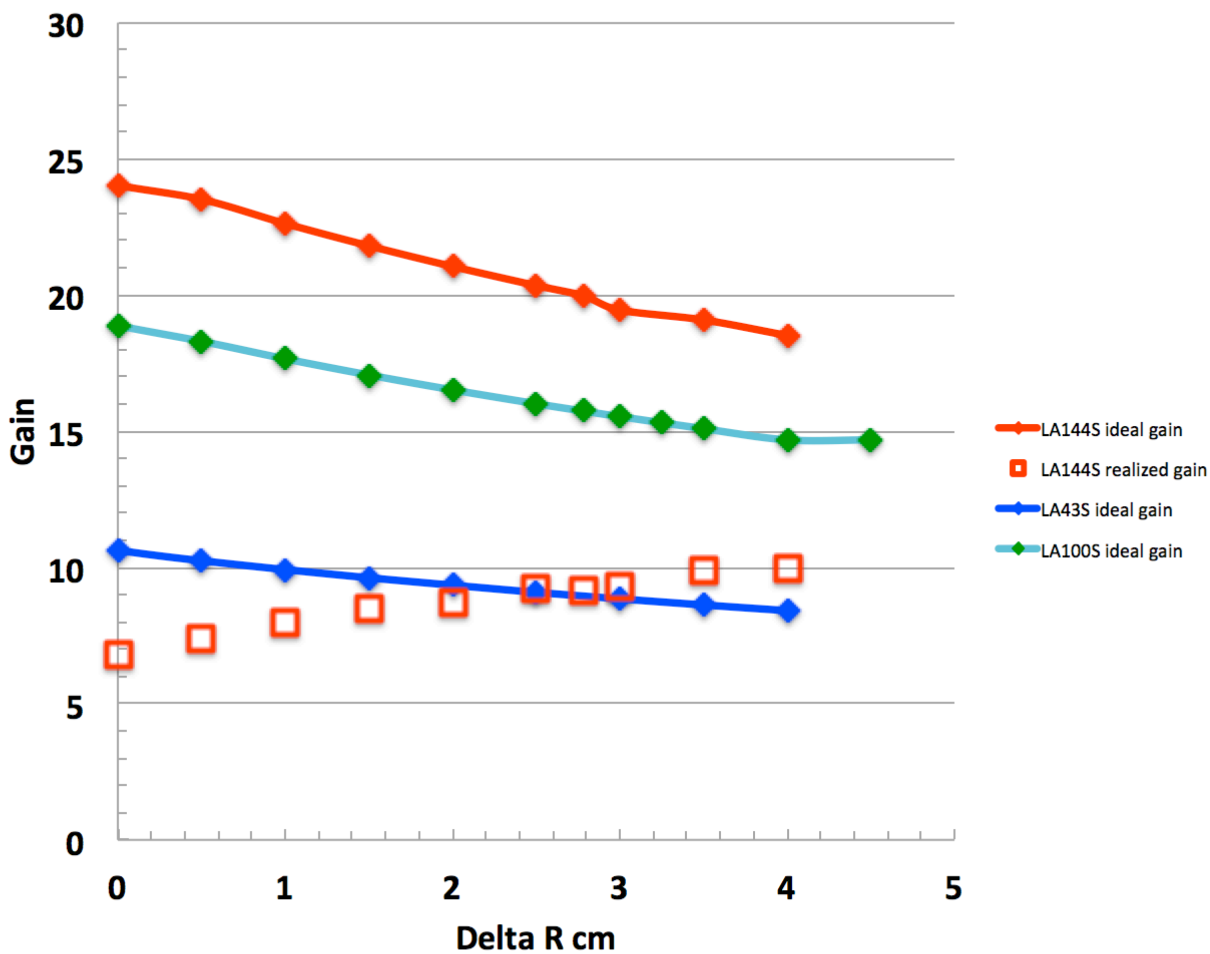

Figure 8. The ideal gain into a *static* 10 nH cavity as a function of the additional radius added to the current RancheroS designs. Three designs are shown with solid curves and diamonds. The effective (realized) gain approach to the ideal gain for the 144 cm generator, as the radius gets larger, whose waveforms were shown in Figure 7, is shown in open squares.

Appendix A: Roxane

The code used in these simulations was the LANL Eulerian AMR code Roxane. The AMR scheme used in Roxane resolves the cells at every interface between materials to the same size. Unlike some other Eulerian AMR codes (LANL's Rage code for instance), all interfaces are resolved to the same cell size. So if the simulation resolved the aluminum-SF6 gas interface to 500 um as was done here, the HE-aluminum interface was also resolved to the same 500 um, as was any other interface. Material temperatures in this type of simulation never get high enough that radiation transport is important. Material strength in the metals uses the Steinberg-Guinan model. No strength was present in the SF6 gas. For these simulations no insulator was present between the two walls of the power flow channel although an insulator is always present in real experiments. Resistive diffusion is used by Roxane. The resistivity of the aluminum came from a table produced by Sandia National Laboratory (SNL), with a resistivity multiplier of 1.44x applied to the pure aluminum table to account for the 6061 aluminum alloy used in the real parts. The input glide plane, not shown in Figure 2, is naval brass and used a 4x multiplier on the SNL copper table. LANL's Sesame tables were used for the equations of state for the metals, with a Gamma law EOS (gamma = 1.3) for the SF6. A reactive burn JWL model was used for the PBX-9501 HE charge inside the armature. The armature had 6 mm diameter detonators every 18 mm represented by already burned PBX-9501, rather than trying to actually model the real slapper-detonator assemblies in detail. An existing void in the HE where the detonator assembly circuit board ends in the real HE assembly was included in the simulations. The resolution of the simulations was 500 um, which is known to be marginal in this simulation, resulting in under-estimates of the peak current and over-estimates of the diffusion into the metal, particularly for the smaller generator. This effect is estimated to be of order 10% for the LA43S system. In the pressure clamped region for the larger generators the resolution is expected to result in a smaller error. Later simulations should revisit this resolution issue, to ensure that the simulation results are converged and that the physics limitations of the systems are as analyzed here.

References:

1. *LA43S-L1 preshot Roxane Predictions LA-UR-15-29079*, R. G. Watt

2. *Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane LA-UR-16-23924,* R. G. Watt

3. *Current drive behavior of LA43S into a 10nH load under photographic enlargement: An attempt to produce 100MA current from 12MA seed*, R. G. Watt 160723

4. *First cut optimization of the current rise after geometric optimization of the stator inner radius profile guided by an 8MA, LA43S into a 10 nH load,* R.G. Watt 160723