The Path to 100 MJ Ranchero Experiments

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Abstract— **Ranchero is the name given to a class of Los Alamos coaxial flux compression generators (FCGs) that are detonated simultaneously along the cylindrical axis. An experiment was reported at MG-XIV in which a Ranchero FCG produced 76 MA peak current, and in MG-XV a design was presented which was intended to overcome a weakness uncovered in the 76 MA test. The name used for the new Ranchero configuration is "Ranchero-S", and that improvement has now been successfully tested. The results of the test are presented in detail in another paper in this conference. This paper reports on scaling studies that are benchmarked by recent experiments, and which demonstrate the approach that would be taken to extend the Ranchero-S performance to levels of 100 MJ and 1.5 Weber. The primary scaling parameter for achieving larger currents is increasing the circumference of the FCG. Detonation systems are available in lengths of 0.43 m, 0.72 m, 1.0 m, and 1.44 m. The longer FCGs can operate with lower initial current for any given peak current and load, which allows them to be less effected by early time back pressure. However, at very high initial current, the effect of having a substantial field operating on a long armature over a substantial time can be seen. As diameter is increased, the flux compression time is increased if the initial inductance is held constant. The flux compression time can be held constant as radius is increased by keeping the armature to stator gap constant, with the result that the ideal gain is reduced for a given module length. The various possibilities are presented, with an emphasis on operating at current levels that approach the limits imposed by armature kinetic energy versus magnetic pressure. Another key feature in performing 100 MJ experiments is the existence of a booster generator which can produce seed currents well in excess of the three to four MA that can be delivered by the 2.4 MJ capacitor bank available at the Los Alamos explosive pulsed power firing facility. The MK-IX generator, which has been used in many experiments previously reported, has potential for producing the necessary seed current. However, a new booster FCG is being developed for that purpose, which will employ modern machining techniques to replace labor intensive methods required by the MK-IX fabrication. This FCG is called the MK-X, and the first test of this device is imminent. Either the MK-IX or the new MK-X booster will need further experimentation to demonstrate the capacity for delivering the approximately 2.5 Weber flux to a Ranchero FCG that projections in this paper require for the full 100 MJ, 1.5 Weber performance.**

Keywords—Ranchero, Flux Compression Generator

I. INTRODUCTION

Ranchero FCGs have been described in several Megagauss conferences, which will be cited here as appropriate. In this paper experimental and computational work are pulled together to make projections to very high performance systems. The original thrust of the paper was showing how Ranchero generators could be scaled to generate 100 MJ, which was a convenient round number in a high energy range. The original conference abstract noted that 100 MJ could be either 140 MA in 10 nH or 120 MA in 14 nH, as examples. The target for the presentation ultimately was the unique set of round numbers, 100 MJ and 1.5 Weber. That is 133 MA in 11.25 nH. In our presentation at this conference, significant milestones in Ranchero development were noted, and most of these are discussed in detail in a 2012 Los Alamos Status Report [1]. Since 2012, further examination of the high current test results given in the status report have focused on an emerging problem at the location of the output glide plane. A minor flaw could be seen in post shot calculations but it was not noticed immediately. The issue was discussed at the Megagauss XV conference in 2016 [2], along with a suggested solution that eliminated the output glide plane all together. Additionally, a paper by Haroz and others in this conference [3] shows the results of a test of the Ranchero-S FCG with a dynamic load. In this paper we discuss briefly two possible ways that the original coaxial Ranchero design could be scaled up to the 100 MJ level, and then focus on what we believe is the best approach based on pursuing the Ranchero-S configuration. Information in two computational surveys [4, 5] are the primary basis for the extrapolations made here. That work describes a system that could generate ~70 MJ in a 10 nH load, and we have further extrapolated that to a current ~13% higher in a 11.25 nH load. Very interesting observations can also be made about the efficiency of conversion from armature kinetic energy (KEA) to increased magnetic energy in the load (ΔMagE), and there is some evidence that this parameter could be optimized.

II. WASTE INDUCTANCE

Through the years of Ranchero testing, we have performed a "figure of merit" evaluation that has evolved to the form: [(LFCG + Lload) x Iinitial]= (Lfinal load + Waste L) x Ifinal, where LFCG is the initial inductance of the FCG, Lload is the inductance associated with load and transmission lines, Iinitial is the initial current in the FCG, Lfinal load is the inductance associated with the load and transmission lines at peak current, and Ifinal is the measured peak current. This is simply the flux conservation statement with the "Waste L" being whatever

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cannot be accounted for at peak current by known inductances. Rewriting, Waste L = [(LFCG + Lload) x Iinitial]/ Ifinal] - Lfinal load. In the following material, this evaluation has been applied to both experimental data and computational results to evaluate performance of various configurations.

III. SCALING ORIGINAL-DESIGN MODULES TO 100 MJ

The 2012 status report, which pre-dates Ranchero-S designs, includes a table that provides scaling information for Ranchero FCGs of the original design that have glide planes at the output. The basic scaling parameter in the tables was the diameter, and modules of 0.43 m, 1.0 m, and 1.4 m in length were considered. Waste L had been estimated from earlier experimental results, and this was scaled along with the module length and diameter. The table projected that a 150 cm circumference (48 cm diameter) Ranchero, 1.4 m long, with a flux compression time of 27 µs could deliver 150 MA to a 10 nH load (112 MJ) given an initial current of 22 MA. The high explosive (HE) charge would have a mass of ~180 kg. After the result of the test referred to as Ranchero LA-43-2 which generated 76 MA but developed an aneurism at the output glide plane, we considered two ways to operate original models of Ranchero at high current. The first consideration was to use less conservative glide planes, such as those shown in our MG-VII paper [6]. This would minimize or eliminate the thin and reduced-diameter contact point between the armature and output glide plane. However, this glide plane was not used on end-output Ranchero FCGs to begin with because in incurs considerable risk of cutting the output insulation. The proper functioning of this glide plane is highly dependent on exact positioning of the HE with respect to the glide plane, and requires complete faith in hydrodynamic calculations after magnetic field is applied to the problem. Even though 2D MHD codes can now provide calculations in which there is increased confidence, high precision assembly would still be required and the option is considered risky. Another option for scaling up our original Ranchero configuration would be to settle for performance at the 76 MA level where the problem was first observed. In this case, one would be operating at the level of 79% of 1 MA/cm circumference, and diameter would be increased accordingly. For this assumption, the 150 cm circumference FCG described above would be only capable of 120 MA, which would be ~72 MJ with a 10 nH load instead of 112 MJ. To compensate, a 190 cm circumference would be used for 150 MA applications. To maintain the 27 µs compression time with the increased diameter, the initial inductance would drop to 81 nH for a 1.4 m long module. Assuming the same losses as in the status report, 29 MA seed current would be required to produce the 150 MA in the 10 nH load, and the HE charge would have a mass of 384 kg. While either of these methods should produce the current required to reach the 100 MJ level in 10 nH, they each have undesirable aspects..

IV. SCALING RANCHERO-S CONFIGURATIONS

Prior to securing funding for a Ranchero-S configuration experiment, it was important to make careful assessments of the design to assure that it could perform at increased current levels. A detailed computational study was commissioned that resulted in two reports [4, 5]. The goal of the study was to show that the S model FCGs would operate with substantial load at or above the 1MA/cm-circumference level, which has been a rule of thumb performance expectation for FCGs. The baseline Ranchero-S design has an output conductor circumference of 83 cm, and we posed the question to MHD modeling personnel in the following terms. Can a Ranchero-S FCG deliver 100 MA to a 10 nH load? This question assumed that the 1MA/cm level could likely be surpassed to some extent. The resulting answers are very interesting, and constitute the information currently available to show how to scale S profile Rancheros.

A. Maximum Performance from the 43-S Configuration

When the above question was posed, it was assumed that an extended length Ranchero-S FCG would be the likely candidate to produce the 1 Weber result we were looking for. However, the baseline module with a 43 cm coaxial section (43-S) was already set up to run on the Roxane 2-D MHD code, and for an initial look, that problem was run with three size loads and a range of seed currents. There are many interesting aspects of the results of those baseline calculations, but the emphatic answer to the question was "no" for the 43-S Module. Fig. 1 shows a summary of the results from the report [4]. In summary, for a 1 nH static inductance load, current slightly over 1 MA/cm could be achieved with a 6 MA seed current, but larger seed currents resulted in smaller peak currents. For 5 nH loads ~1 MA/cm could be generated with an 8 MA initial current level, and peak current was less for larger seed currents. And finally, the 10 nH load requested never allowed current above ~73 MA (0.9 MA/cm). There is a great deal of information that can be gleaned from these results, and a few highlights are noted here. For small loads, gain goes up as you would expect with seed current, but there is a level at which the magnetic pressure stops the armature, and beyond that, peak current is reduced because the armature is stopped with an increasing amount of inductance remaining in the un-compressed volume. For the 10 nH load, gain increases through the range of initial currents explored, although one can tell from the fig. that the increase in peak current is proportionally less than the increase from 10 to 12 MA in seed current. Reference [4] points out that at 8 MA initial current the gap barely closes in the "bell" section, and by

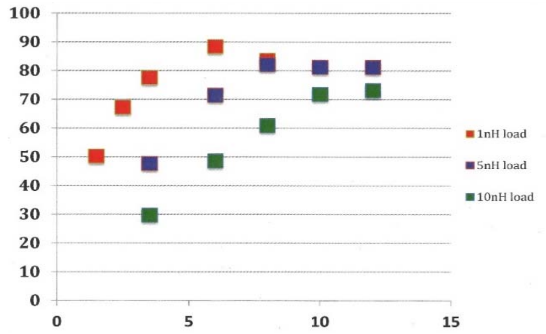

Fig. 1.Peak Current (vertical axis in MA) calculated for 1 nH (red), 5 nH (Blue), and 10 nH (green) static inductance loads as a function of initial current (horizontal axis in MA).

12 MA a substantial gap is observed that never closes. This report also reveals another parameter of interest. There is a section in the report dealing with system energetics. An oversight made in the preparation of the report leads to the statement that for the 8 MA seed current, 10 nH load case, 74% of the armature kinetic energy (KEA) is converted to magnetic energy (MagE). The oversight was failing to subtract the initial magnetic energy from the final, but the conversion ratio on that run was still a very respectable 43% with the oversight corrected. The report plots out the energy partitioning between KEA and magnetic field, and sparked further investigations as this report was prepared. Table 1 summarizes the results for the 10 nH load calculations. Once the initial magnetic energy is subtracted off, the 8 MA case has only 43% KEA converted to magnetic energy. However, the conversion ratio for the 10 MA seed current case is 57%. These numbers involve approximations for KEA and may not have high accuracy, but achieving a transfer efficiency of ~50% would be outstanding, especially considering that removing 50% of the KEA would slow the speed of the armature to 70% its initial value. Some increase of the time to peak current is noted in the paper, but it is not severe. Reducing armature velocity below 70% could make the pulse time of the FCG longer than desirable. The additional feature that is noted here is that there is a maximum in the values for conversion ratios. 10 MA seed current produces a larger increase in magnetic energy than 12 MA. The existence of a peak suggests that there may be a possibility for optimizing this parameter..

Table 1 Summary of 43-S calculations with 10 nH load. KE_A is the armature kinetic energy which is estimated to be 36 MJ in all cases. ΔMagE is the calculated increase of magnetic energy. Note that the conversion ratio has a peak at 57% for the 10 MA seed current case.

Initial Current (MA)	Initial MagE (MJ)	Peak Current (MA)	Final MagE in 10 nH (MJ)	ΔMagE (MJ)	Conversion ratio: ΔMagE / KE_A (%)
3.5	0.59	30	4.5	3.91	11
8	3.1	56	18.6	15.5	43
10	4.8	71	25.2	20.4	57
12	6.9	73	26.7	19.8	55

B. *Increasing the length to achieve 100 MA*

Report [5] continued the search for a 1 Weber source with a 10 nH load. Ranchero FCGs with coaxial detonators up to 1.4 m have been fielded multiple times [1] and Roxane computations were performed with Ranchero modules up to 144-S. This FCG would be constructed by adding length to the coax section of the 43-S module. Fig. 2 shows a picture of 43-S and 144-S. In the next round of computations, the two modules shown in the fig., as well as modules designated 72-S and 100-S, were considered. In that set of calculations, the initial current was set to 12 MA and the load to 10 nH for all runs. The results are summarized in Table 2. The current from the 43-S run has a break at 60 MA, which is shortly before other runs peak, and then slowly (over more than 10 µs) ramps up to 68 MA. The authors are suspect of such late time performance, and elect to take the 60 MA peak as the most that can be expected on such a test. The other results reach peaks at 77-81 MA, which range from 0.92 to 0.98 MA/cm. The. waste inductance is seen to climb from 9 nH to 26 nH, and the conversion from KEA to MagE peaks for the 72-S configuration. In practice it would be evaluated whether the increase of 4 MA in peak current (~3 MJ magnetic energy) would be worth the extra HE mass that went with the extra 72 cm armature length. This set of calculations never attempted to run the problem with less initial current, but it is recognized that there might be a path to more peak current with less initial current, and this will be left for future computations.

C. *Increasing Radius to Achieve 100 MA*

The next step in examining paths to 100 MA was to increase the radius of the four FCGs examined in the last study by 2 cm. Additionally, the decision was made to keep the pulse length roughly the same by keeping the initial gap between the armature and stator the same for all cases. Because the initial inductance of these devices goes as the natural log of the ratio of outer radius to inner radius, the inductance of the FCGs so designed would be reduced. In the this study, the decision was made to add length to each module to make up for the lost initial inductance, and thereby keep the ideal gain the same as that for the standard length and radius generators examined in the previous step. The results of this

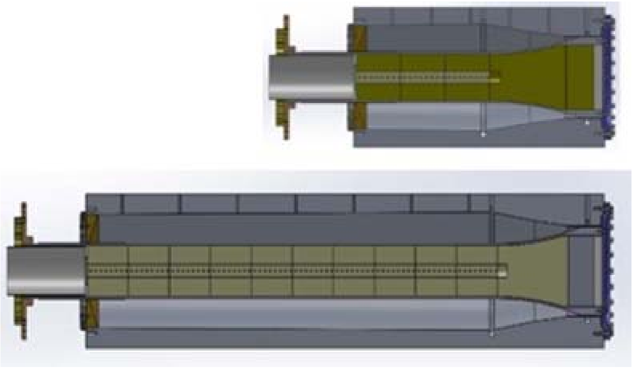

Fig. 2. Ranchero FCGs with 43 cm and 144 cm coax sections, designated Ranchero 43-S and 144-S respectively

Table 2. Results from survey of Ranchero-S FCGs with coaxial lengths of 43, 72, 100, 1nd 144 cm. L0 is the initial inductance, Ip is the peak current, and the other parameters are as defined in the text.

FCG	L0 m(H)	Ip (A)	Waste L (H)	ΔMagE / KE_A	Peak MagE (J)
43S	8.60E-08	6.00E+07	9.20E-09	3.08E-01	1.80E+07
72S	1.26E-07	7.70E+07	1.12E-08	3.82E-01	2.96E+07
100S	1.70E-07	8.00E+07	1.70E-08	2.80E-01	3.20E+07
144S	2.30E-07	8.10E+07	2.56E-08	1.69E-01	3.28E+07

set of simulations are given in Table 3. The peak current is seen to reach 107 MA in this case with a 144-S configuration with a 2 cm larger radius output slot (13.2 cm + 2 cm = 15.2 cm). The circumference of the output slot, which is the minimum radius at peak current in the computation, is 96 cm, and at this dimension, the current per circumference is 1.12 MA/cm. The gain by adding radius here is significantly increased. Waste L is reduced significantly even though each module is made longer. Table 4 compares peak current and Waste L for the two cases. While this scaling worked, it lacked some practicality due to the fact that each scaling required, in practice, the development of a new length detonator. As a result, one more set of scaling computations were made. In this set, the length of the coax section of all FCGs was set at 144 cm, and the load inductance and initial current remained at 10 nH and 12 MA respectively. The parameter varied in the study was radius, and eight total runs made, increasing the radius by 0.5 cm in each increment. Table 5 shows results from four of the configurations and the last row is an extrapolation for later consideration. Among the calculated values, the peak energy is shown to be ~70 MJ (at 118 MA) which occurs when the radius has been increased by 3.5 cm. There are many fascinating implications of the results. One result, presented graphically in the report [5], shows that while the ideal gain drops as the radius increases, the actual calculated gain increases throughout the range of calculations. However, the calculated gain seems to be flattening off at about 10. The main reason computed gain increases is that the Waste L drops from ~26 nH at the initial radius to ~9 nH at the 3.5 cm increase. Another feature is that the peak current/(cm-circumference) increases slightly as radius increases. Since the magnetic pressure goes with the square of that parameter, the pressure varies from ~60 kb to ~80 kb in the range shown.

Table 3. Results from simulations of Ranchero FCGs with radius increased, but armature to stator gap the same as standard radius modules. Length was added in each case to keep the ideal gain the same as standard modules.

FCG	L0	Ip	Waste L	peak MagE
43S+	8.60E-08	7.00E+07	6.46E-09	2.45E+07
72S+	1.26E-07	8.80E+07	8.55E-09	3.87E+07
100S+	1.70E-07	9.50E+07	1.27E-08	4.51E+07
144S+	2.30E-07	1.07E+08	1.69E-08	5.72E+07

D. Extrapolation to 100 MJ and 1.5 Weber

The 70 MJ result shown in Table 5 is the highest energy calculated in the study, whose goal was to demonstrate that 100 MA could be generated in 10 nH with a Ranchero-S FCG. At this writing, calculations are underway to calculate specifically the endpoint posed by the paper title. For now, extrapolations based on Table 5 have been made to give estimated values for the system required. The last row of the table is labeled “plus 5.7,” and represents a projection of existing results to the increased level given in the paper title. The extrapolation was made in the following way. The first assumption was that the current per circumference would not increase beyond the 1.12 MA/cm level, even though the trend in the results are for it to go up slightly. Since 100 MJ at 1.5 Weber is a unique set of parameters, 133 MA at 11.25 nH, the extrapolated radius for the output slot was increased to a circumference given by 133 MA/1.12 MA/cm which is 118 cm. This represents a total increase of 5.7 cm from the original 13.2 cm. The dimensions of that FCG give an approximate initial inductance of 164 nH. Since ref. [5] shows the calculated gain curve flattening out at 10, the assumption was made that ten would be the gain calculated for the extrapolation. Thus, 13.3 MA would be the initial current required to reach 133 MA. However, the load stipulated is actually 11.25 nH, not 10 nH, and so the gain would be reduced and the initial current would have to be scaled up. To make that scaling, the projected waste L of ~6 nH would have to be incorporated, and the scaling ratio would be (11.25 +6)/(10+6) = 1.08. That is, the initial current would be 14.3 MA. There is no assurance that this scaling is highly accurate, but the extrapolations are for less than10% increase in initial current and 13% for final current at the same current/circumference. This is at least a good starting point for calculations in progress at the time of the conference which will better define the system. The one extra value that is worth extracting from this extrapolation is the weight of the HE that would be required. All Ranchero experiments and calculations use a 0.6 cm thick Aluminum armature. Using this value, and the 5.7 cm addition to radius, an approximation of ~200 kg for

HE mass can be made. Drawings of LA-43S, LA-100S, and the 100 MJ, 1.5 Weber Ranchero are given in fig. 3.

V. CONCLUSIONS

A system capable of producing 70 MJ magnetic energy has been defined using a well calibrated MHD code and we have extrapolated the dimensions to extend the results to 133 MA in 11.25 nH based on the calculated values. Extrapolations show that this efficient Ranchero-S would require ~200 kg HE and would require 14.3 MA initial current (2.3 Webers). Further computations are in progress to refine the actual dimensions required. In addition, two techniques are discussed for generating the 100 MJ and 1.5 Weber using Ranchero FCGs of the original (not swooped) design. A design using less conservative glide planes could be implemented, but this is seen as too risky. A brute force approach could also be implemented which increases the radius to allow a current/circumference of only 79% the initial expectation. The design would need a 190 cm circumference output slot to carry 150 MA, and would yield too much decrease in gain with too large an increase in HE (384 kg). In the paper, considerable attention was also focused on the efficiency of converting KEA to MagE. The simulation revealing a 70 MJ design asserted a 41% conversion ratio, and some calculations reached as high as 57%. In addition, in some of the simulations in which parameter ranges were explored, there appeared to be peak efficiencies within the parameter range. This could indicate an optimum could be found, and it may be possible to find an optimum energy transfer ratio for specific cases. We have suggested that 50% would be ideal and achievable. If each segment of the armature has been slowed to 70% of its original speed when it contacts the stator, then 49% of the KEA would be consumed without lengthening the pulse length inordinately. Finally, a helical booster FCG that will be able to supply ~2.5 Weber initial flux to the full scale Ranchero-S will be required in order to operate Rancheros in the range if multiple tens of mega-joules. A new design helical FCG for such purposes is currently being designed at Los Alamos. The generator will be designated the MK-X and be a modern replacement for the Los Alamos MK-IX generator that would routinely supply 1.6 MJ on systems in the 1980s and 1990s. The MK-X will be manufactured using machining operations to replace labor

Table 4. Comparison between standard modules and modules with increased radius of 2 cm (indicated by "+"), plus enough added length to keep compression time the same as standard modules. Ip is the peak current

FCG	Ip (A)	Waste L (H)	FCG	Ip(A)	Waste L (H)
43S	6.00E+07	9.20E-09	43S+	7.00E+07	6.46E-09
72S	7.70E+07	1.12E-08	72S+	8.80E+07	8.55E-09
100S	8.00E+07	1.70E-08	100S+	9.50E+07	1.27E-08
144S	8.10E+07	2.56E-08	144S+	1.07E+08	1.69E-08

Table 5. Results from increasing the radius of a 144-S Ranchero by 1, 2, 3, 3.5, and 5,7 cm. L0 is initial inductance, Ip is the peak current, I/C is peak current/circumference, Peak MagE is the energy in 10 nH at peak current, ideal gain is the FCG gain with no losses, and calculated gain is the calculated ratio of final to initial current.

FCG	L0	Ip	I/C (MA/cm)	Peak MagE	Ideal Gain	calculated gain
0	2.30E-07	8.10E+07	0.98	3.28E+07	24	6.75E+00
plus 1	2.17E-07	9.50E+07	1.07	4.51E+07	22.5	7.92E+00
plus 2	2.00E-07	1.04E+08	1.08	5.41E+07	21	8.67E+00
plus 3	1.85E-07	1.12E+08	1.10	6.27E+07	19.5	9.33E+00
plus 3.5	1.80E-07	1.18E+08	1.12	6.96E+07	19	9.83E+00
plus 5.7	1.64E-07	1.33E+08	1.12	8.84E+07	17.4	1.11E+01

intensive wire windings that were used on the MK-IX. The first application for the MK-X will be to supply ≤ 8 MA to a 43-S Ranchero to drive a dynamic load. It has been shown that current in this range is approximately the maximum that will be useful with the KEA available from the 43-S design. A note in closing is that as performance of Ranchero FCGs approaches limiting conditions, the use of a copper stator could reduce losses and enhance performance.

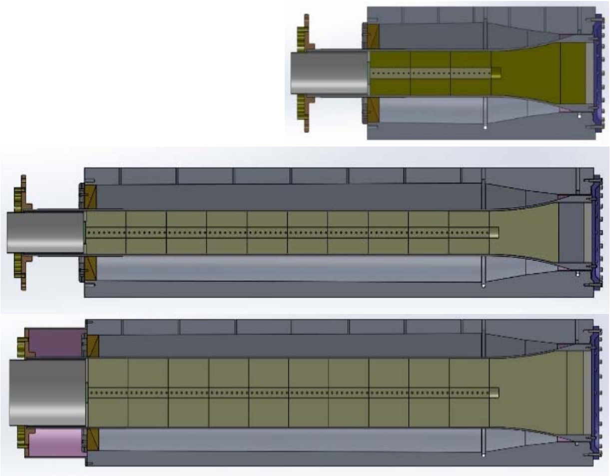

Figure 3. Scale drawings of, from top to bottom, 43-S, 144-S, and the 100 MJ, 1.5 Weber projection.

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