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Title: Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane

Author(s): Watt, Robert Gregory

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# Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane

R. G. Watt, 5/30/2016

The Ranchero Magnetic Flux Compression Generator (FCG) has been used to create current pulses in the 10-100 MA range for driving both "*static*" low inductance (0.5 nH) loads[1] for generator demonstration purposes and high inductance (10-20 nH) imploding liner loads[2] for ultimate use in physics experiments at very high energy density. Simulations of the standard Ranchero generator have recently shown that it had a design issue that could lead to flux trapping in the generator, and a non-robust predictability in its use in high energy density experiments. A re-examination of the design concept for the standard Ranchero generator, prompted by the possible appearance of an aneurism at the output glide plane, has lead to a new generation of Ranchero generators designated the RancheroS (for swooped). This generator has removed the problematic output glide plane and replaced it with a region of constantly increasing diameter in the output end of the FCG cavity in which the armature is driven outward under the influence of an additional HE load not present in the original Ranchero. The resultant RancheroS generator, to be tested in LA43S-L1[3], probably in early FY17, has a significantly increased initial inductance and may be able to drive a somewhat higher load inductance than the standard Ranchero. This report will use the Eulerian AMR code Roxane to study the ability of the new design to drive *static* loads, with a goal of providing a database corresponding to the load inductances for which the generator might be used and the anticipated peak currents such loads might produce in physics experiments. Such a database, combined with a simple analytic model of an ideal generator, where d(LI)/dt = 0, and supplemented by earlier estimates of losses in actual use of the standard Ranchero, scaled to estimate the increase in losses due to the longer current carrying perimeter in the RancheroS, can then be used to bound the expectations for the current drive one may apply to any load assembly in future experiments.

Figure 1 shows a comparison between the standard Ranchero and the new RancheroS generator, both with a 43 cm long straight section, driving a low inductance load formed of a simple groove into which a Faraday Rotation current probe can be placed to monitor performance . The FR groove in the standard Ranchero is about 0.5 nH while that in the RancheroS is more like 0.3nH. The FCG initial inductance of the Ranchero generator is ~ 56nH, while that of the RancheroS is ~ 87nH. The *static* loads used in this report are additional cavities similar in concept to the FR grooves, but larger, with an inner radius equal to that of the output TL inner radius, and a much larger outer radius adequate to match the desired inductance within a reasonable length (10 cm or less). The additional loads are not shown in the CAD models in figure 1. They were added from Roxane primitives to avoid the need to build a new Solidworks/OSO model for each configuration. The outer load radius was about 19 cm in most cases unless that was so large that the small length of the extra cavity at low inductance created problems with colliding blowoff from each side that resulted in code issues, in which case the cavity was made longer but not as tall radially, to preclude colliding material problems. In any event, the inductance reported by the code matched that desired to around 1%.

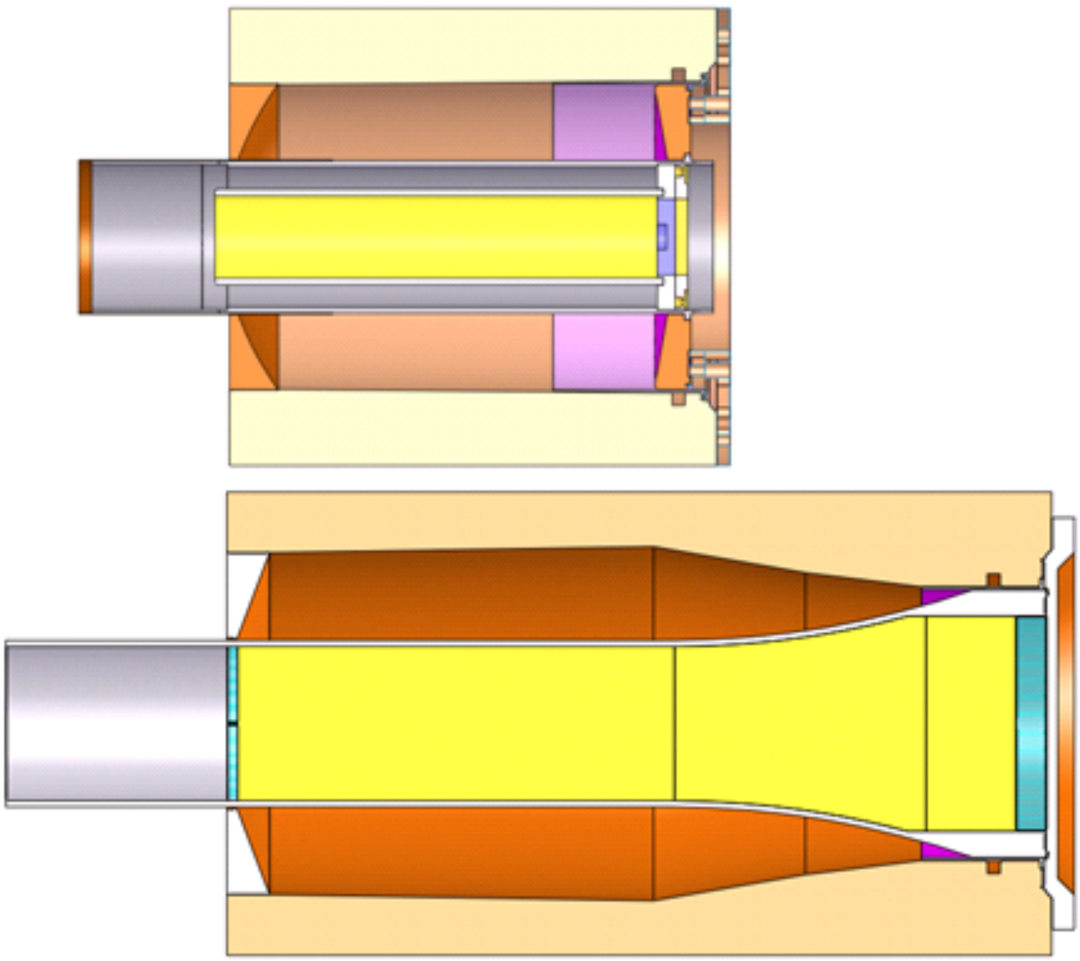

Figure 1. A comparison between the 43 cm generator used in LA43-2[1] and the "43 cm" swooped generator LA43S, both driving an FR groove load. The parts are brought into the code from a SolidWorks[3] model, via OSO[4] .

Table 1 lists some of the generator specifications

| | |
|---|---|
| Designation | LA43S |
| Stator | 6061 T6 Al, 22.86 cm OR, 81 cm long |
| Stator (input IR, break IR, TL OR) | 16.88 cm / 17.48 cm / 13.5128 cm |
| Armature, dets & length | 24x2 dets at 18mm spacing, 43cm uniform radius section |
| Armature radii | 8.22/7.62 cm uniform section, 35 cm swoop to 13.218 cm OR (TL IR) |
| Detonators | 2x24each, slappers, on 18 mm centers |
| HE | PBX 9501 |
| TL output radii, length to CJ | 13.5128/13.218, 6.65 cm |
| Insulator | Not used in simulations |
| FCG Input Glide plane | Naval Brass, uniform 20.79$^{o}$ off radial |
| FCG Inductance (Roxane) | 87.1 nH initial (including FR grooves) |
| Desired seed currents | 1.5, 2.5, 3.5, 6, 8, 10, 12 MA |
| *Static* load inductances | 1, 5, and 10 nH |

## Baseline physics behavior from simple analytics

There are many ways to analyze the expected behavior of the system into a *static* load. The simplest, which is probably good to around 10-15%, is just to assume that the entire SF6 filled gap in the FCG body goes to zero volume (zero inductance) at peak current and the only remaining inductance is that of the load, set equal to its initial value. Then in the ideal case, d(LI)/dt = 0 and the peak current is simply the initial seed current times the ratio of the initial total system inductance to the final, load only inductance. This is the best the FCG operation can be. For a 10nH load working with an initial 87nH LA43S generator to create an initial 97nH system, with 3.5MA seed current, this would produce a maximum of 34MA. Unfortunately the system does have losses, and those will eat some of the ideally conserved magnetic flux. The losses are due to both resistivity and heating, and to magnetic diffusion out of the void and into the metal. As a way of looking at limiting cases of loss due to the combination, one can look to previous generator experiments. The 2012 LA43-2 experiment provides a nice example. In that case the generator itself was ~ 56nH and the load was 0.57nH at time zero. A seed current of 3.76MA produced a peak current of 76MA. With an ideal peak current calculated from d(LI)/dt = 0 [i.e. 3.76MA*(56.57nH/0.57nH)] of well over 300MA and a measured peak current of only 76MA it is clear that losses combined with magnetic and material back pressure from the void dominated the behavior, producing an effective inductance at peak current of around 2.8 nH of which only 0.57 nH was from the original FR groove. (In fact, other Roxane simulations suggest perhaps half of the final inductance was due to an aneurism at the output glide plane, which should not occur in the RancheroS.) So it seems that an additional 2.3 nH of equivalent inductance resulted from back pressure, resistance, the suggested aneurism, and magnetic diffusion. Since the resistance and diffusion should be expected to scale with the length of the metal perimeter in which they are occurring, it might make sense to expect , in the worst case, an additional 3.9 nH of effective inductance due to the 1.7x longer perimeter in the no load LA43S case, relative to the no load LA43 case. If this is added to the 10nH initial load inductance at peak current, the peak current might be expected to only reach 3.5MA*(97nH/(10.0 +3.9nH)), or around 24.5MA in the case where losses similar to those of past experience occurs. So from simple arguments a peak current might be expected somewhere between 25MA and 34MA. Those values are worth remembering when examining the results produced from Roxane in the following sections.

## Description of the simulations using the Roxane Eulerian AMR rad-hydro MHD code

Roxane was used to predict the full system behavior of the LA43S generator into 3 *static* loads, 1nH, 5nH, and 10nH. The generator geometry was generated in Solidworks for the machine shop and exported as stereo-lithographic (STL) files for import into OSITO (OSO's modern incarnation). An OSO model was created and imported into Roxane by using the Rage code's setup capabilities for the initial machine cycle. (Rage is another LANL Eulerian AMR rad-hydro code.) Roxane used Steinberg-Guinan strength models for all metals and assumed no strength model for the 9501 or the SF6 gas in the FCG void and the *static* load cavity. The SF6 was treated as a low density (1 atm, 0.00612 g/cc) Al gas with a gamma law model with gamma equal 1.3. Programmed burn was used to detonate the HE from an initial set of 24 "*detonators*" built into the programmed burn model in Roxane. The individual detonators were not intimately modeled, although that capability does exist using the reactive burn model in the code. The void in the HE at the end of the slapper circuit board was not included in the simulations, but an analysis of the effect of that void, using Roxane's reactive burn model has been done, revealing minimal differences in the flux compression history due to it, although differences in the *local* armature velocity history can be seen due to the void when using reactive burn. The Al used the sesame 3720 EOS. Resistivity tables from SNL were used for the Al and brass. A resistivity multiplier of 1.44x on the SNL pure Al resistivity table was used for the armature and stator, which are made of Al 6061. The brass glide plane used the SNL copper table with a multiplier of 4.0x and the brass sesame EOS. The multipliers originated from a metal vendors website. The loads were simple voids similar to the FR groove used to measure the current in a real experiment, albeit larger to produce the desired inductance. The Delrin insulator in the output TL was deleted from the model for these simulations. The simulations were done with a 250um resolution. Figure 2 shows a typical pseudo-color view of the magnetic flux (top) and density (bottom) of an earlier 10 nH, very low seed current (0.376MA) simulation at approximately first motion time for the armature, for visual orientation purposes. The density perturbations seen inside the armature in the lower half of the image are the result of the progressing detonation wave.

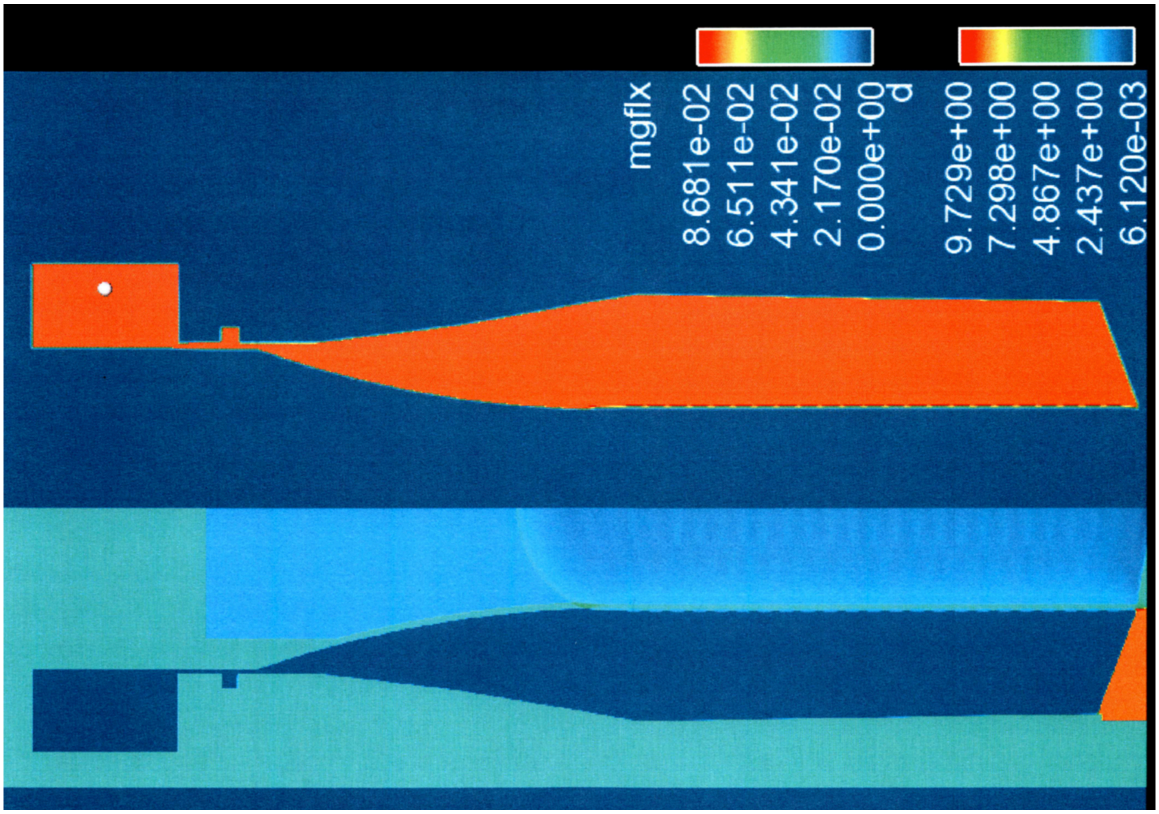


Figure 2. The simulation geometry at first motion, showing the magnetic flux in the entire FCG + 10nH load (top) and density (bottom) near first motion of the armature for an early simulation with a very small seed current (0.376MA). At currents above 50-60MA the load cavity will distort and the load inductance will increase due to the magnetic forces on the metal.

## General overview of results

The current history in the load was monitored in the load void. The detailed time histories will be shown in the next section. For the purposes of this initial overview the current at either the peak or at 89us into the simulation, near where the large loads peaked in time will be given. The 1 nH load typically peaks at about 83-84 us, and the peak for the 10 nH case is delayed to 88-90us depending on the detailed current history behavior. (See figures 4-6 below.) Using the 89us value or that at the earlier peak time provides a common reference for performance. Table 2 gives numbers and figure 3 plots the peak current as a function of seed current for the three load inductances. (A spreadsheet is available from the author for those desiring details for all the runs.)

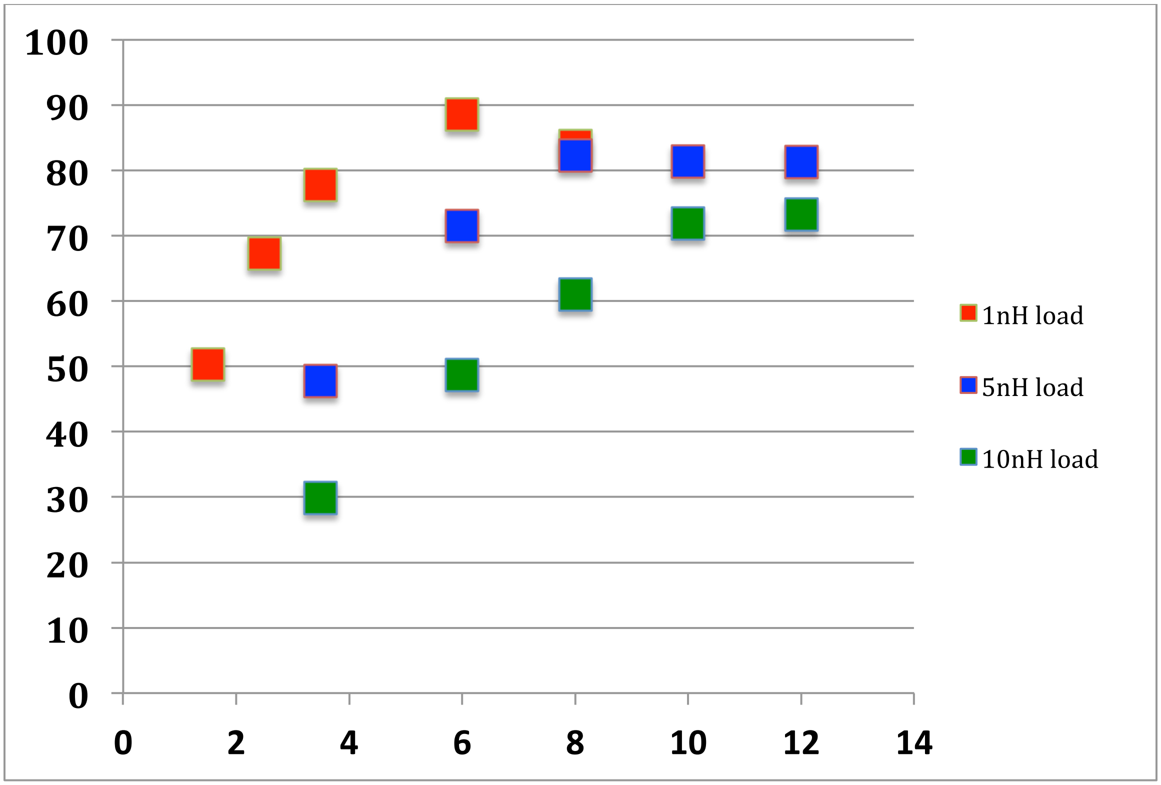

Figure 3. Roxane's LA43S peak currents into various *static* loads.

Table 2. Peak current levels into various loads.

| Load nH | Seed MA | Current MA |
|---|---|---|
| 10 | 3.5 | 29.8 |
| 10 | 6 | 48.7 |
| 10 | 8 | 61 |
| 10 | 10 | 71.9 |
| 10 | 12 | 73.23 |
| 5 | 3.5 | 47.8 |
| 5 | 6 | 71.51 |
| 5 | 8 | 82.22 |
| 5 | 10 | 81.33 |
| 5 | 12 | 81.3 |
| 1 | 1.5 | 50.3 |
| 1 | 2.5 | 67.3 |
| 1 | 3.5 | 77.7 |
| 1 | 6 | 88.5 |
| 1 | 8 | 83.7 |

## Waveforms from the simulations

The behavior of the current pulse depends on the effect of the load on the overall time history of the full system inductance. In the case of a small load inductance the risetime is as fast as it can get based on the armature motion and the peak current is dominated by the losses in the FCG itself. As the load becomes larger, the L/R time increases, the risetime slows a bit, and peak current will eventually be dominated by the load inductance, which can be much larger than the losses and residual FCG inductance. Figures 4, 5, and 6 show the current waveforms in the 1nH, 5nH, and 10nH loads as a function time for all the seed currents used in the survey. For reference and use by 1D codes, the inductance of the LA43S generator driving the 10nH load at 3.5MA seed, where little distortion of the generator from its baseline behavior occurs, is shown figure 7. Finally, note that as the seed current and compression increase, the magnetic back pressure increases which will affect the closure of the bell section which occurs near peak current. In the 10nH load case, this effect becomes dominant around 8-10MA seed and limits the bell closure so that an increase to 12MA seed is not effective in increasing the peak current further. This effect is seen in figure 8 , which shows a comparison between the flux plots at peak current for the 10nH *static* load at 3.5 MA, 8 MA, and 12MA seed.

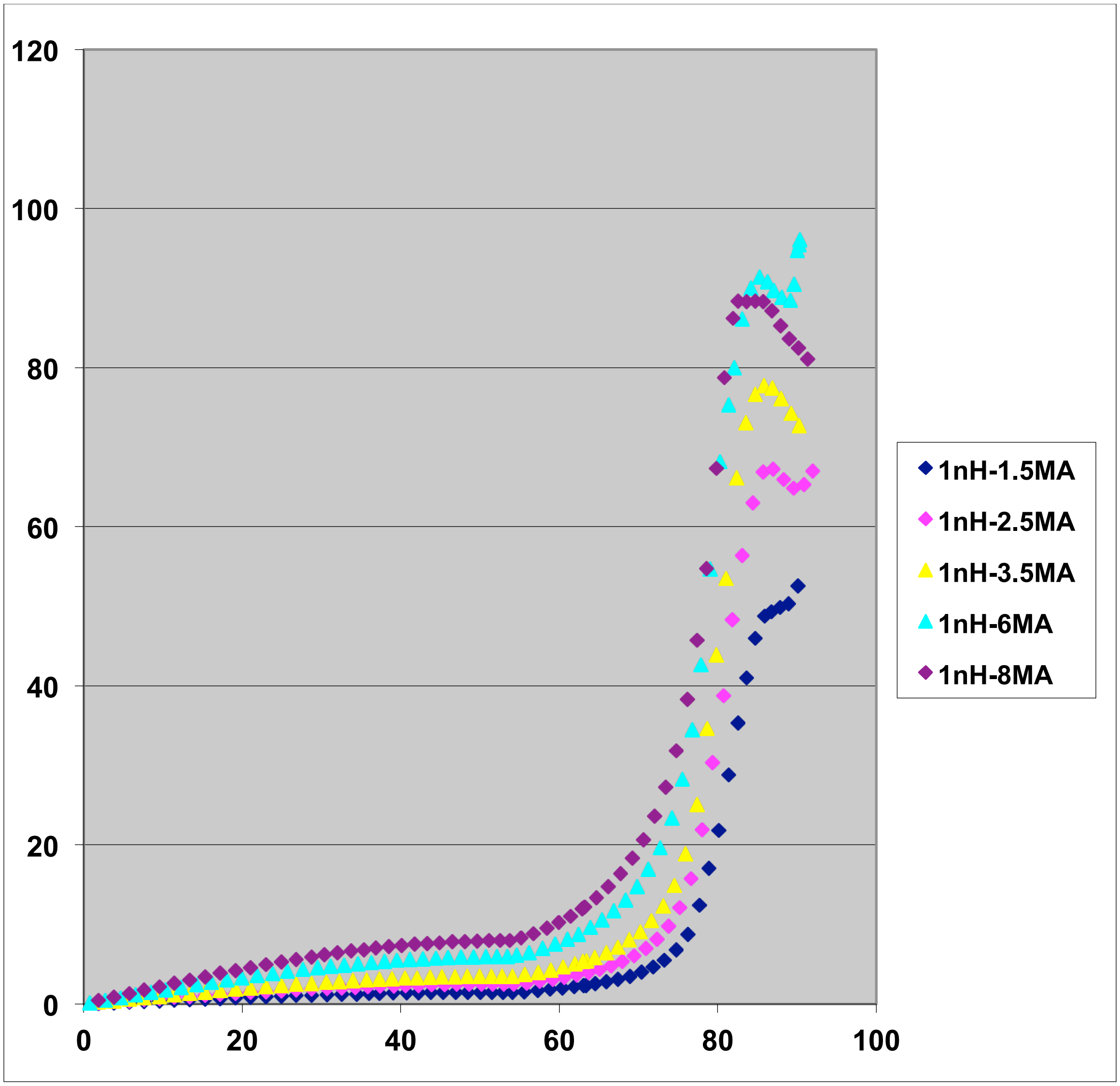

Figure 4. I(t) for various seed currents into a 1nH *static* load.

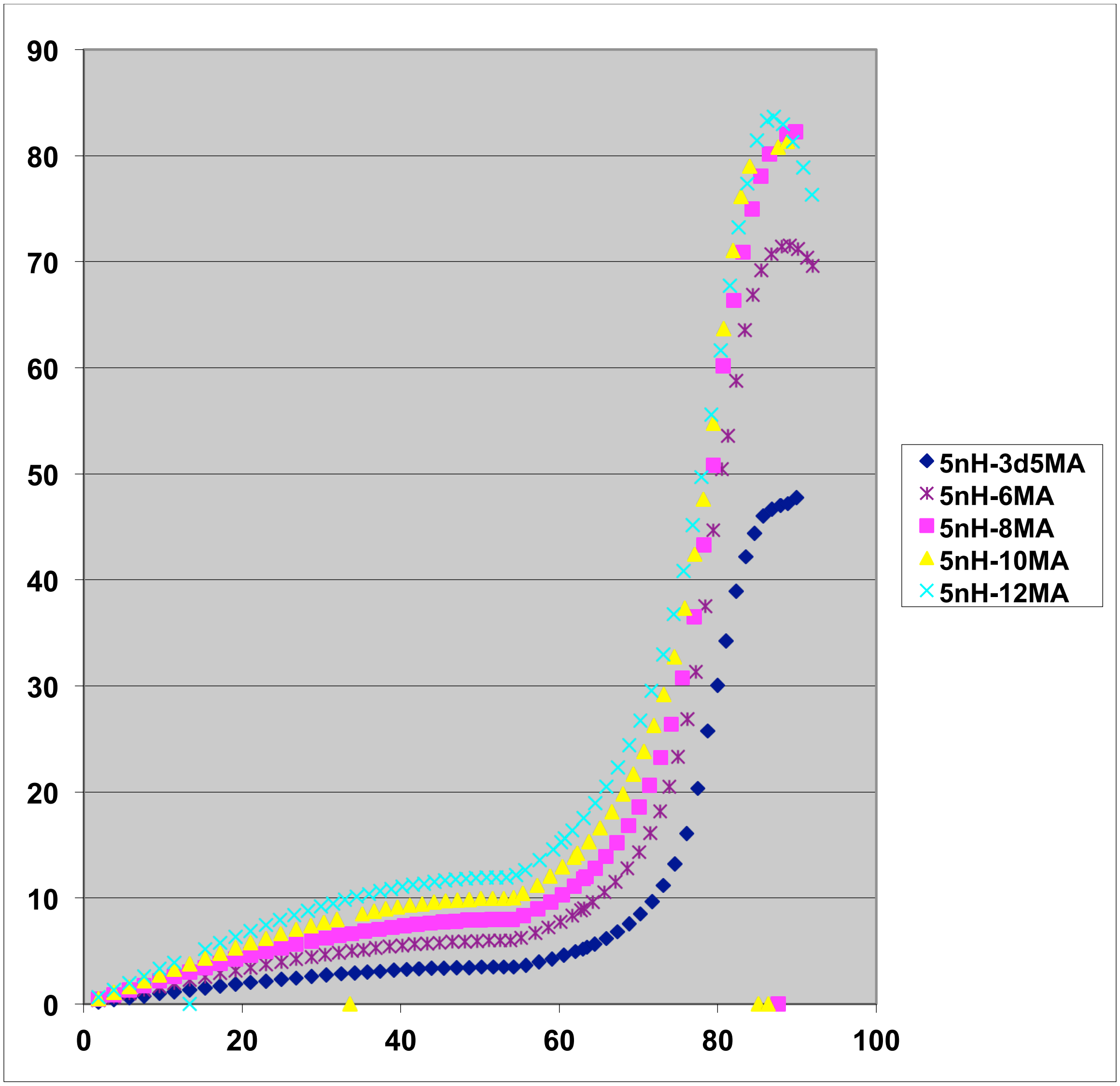

Figure 5. I(t) for various seed currents into a 5nH *static* load.

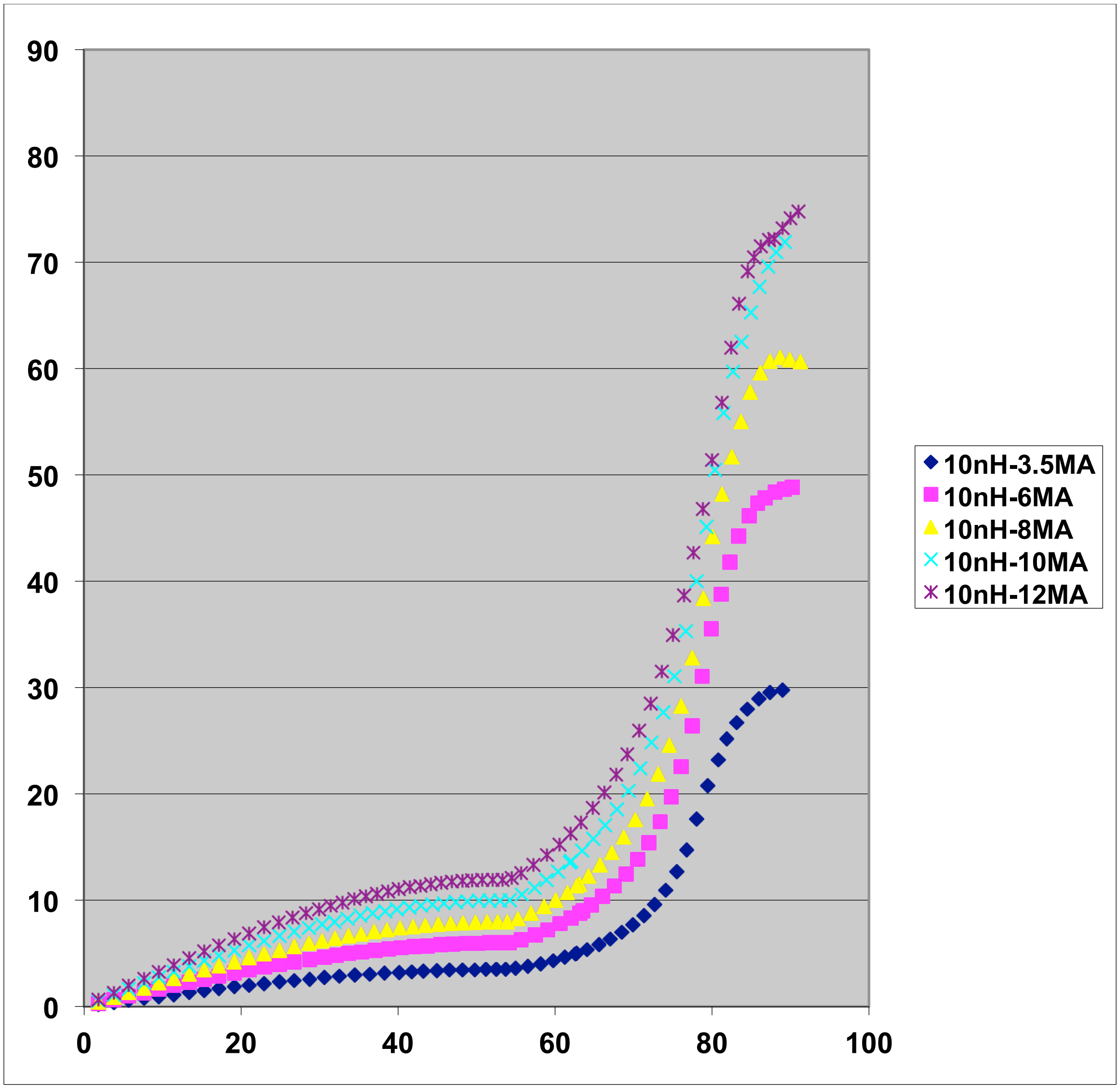


Figure 6. I(t) for various seed currents into a 10nH *static* load.

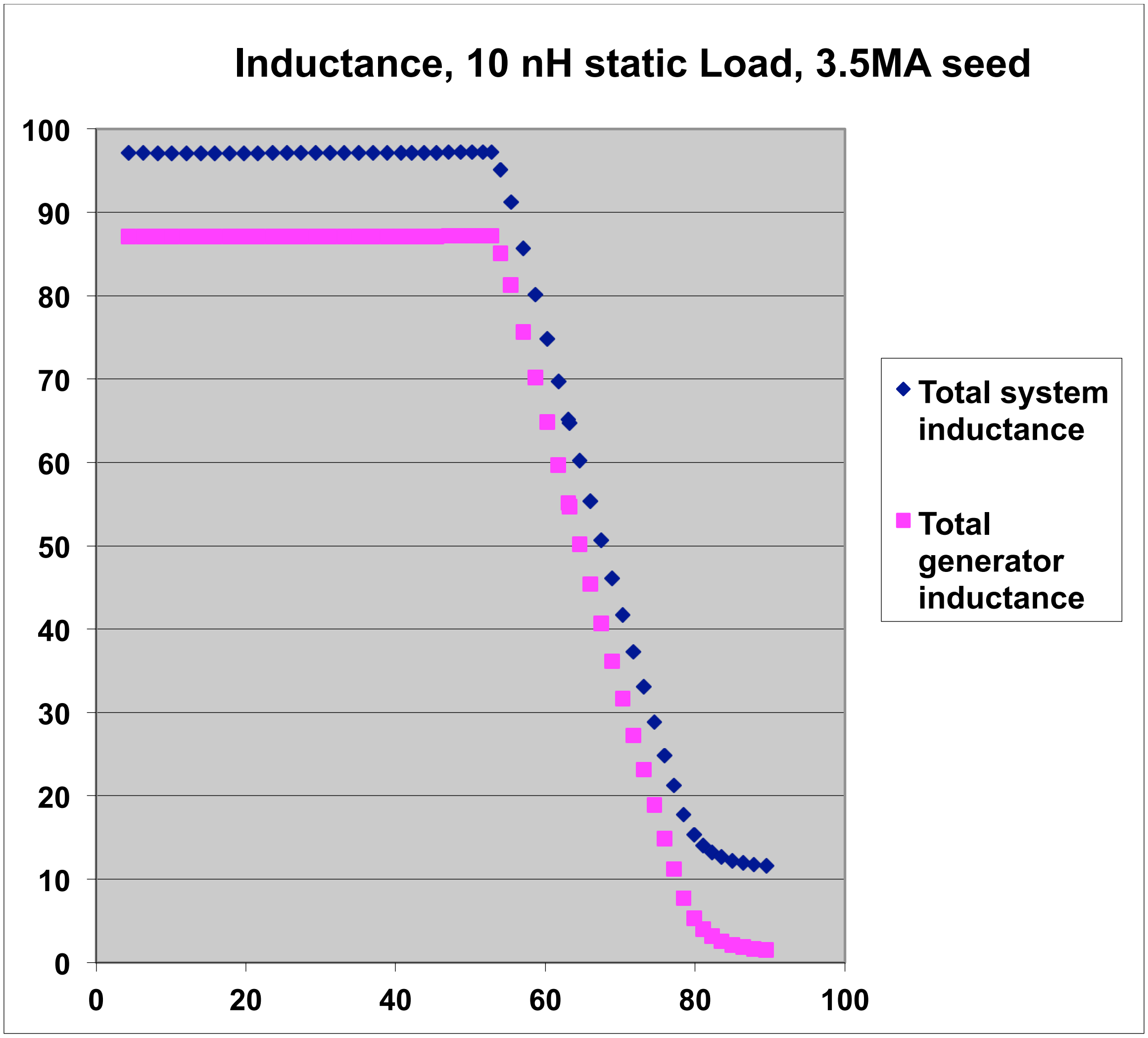


Figure 7. Total system inductance (load + FCG ), blue, and FCG SF6 cavity inductance, magenta, from a 10nH load, 3.5MA seed current simulation, in which minimal load or generator distortion due to excessive magnetic pressure occurs.

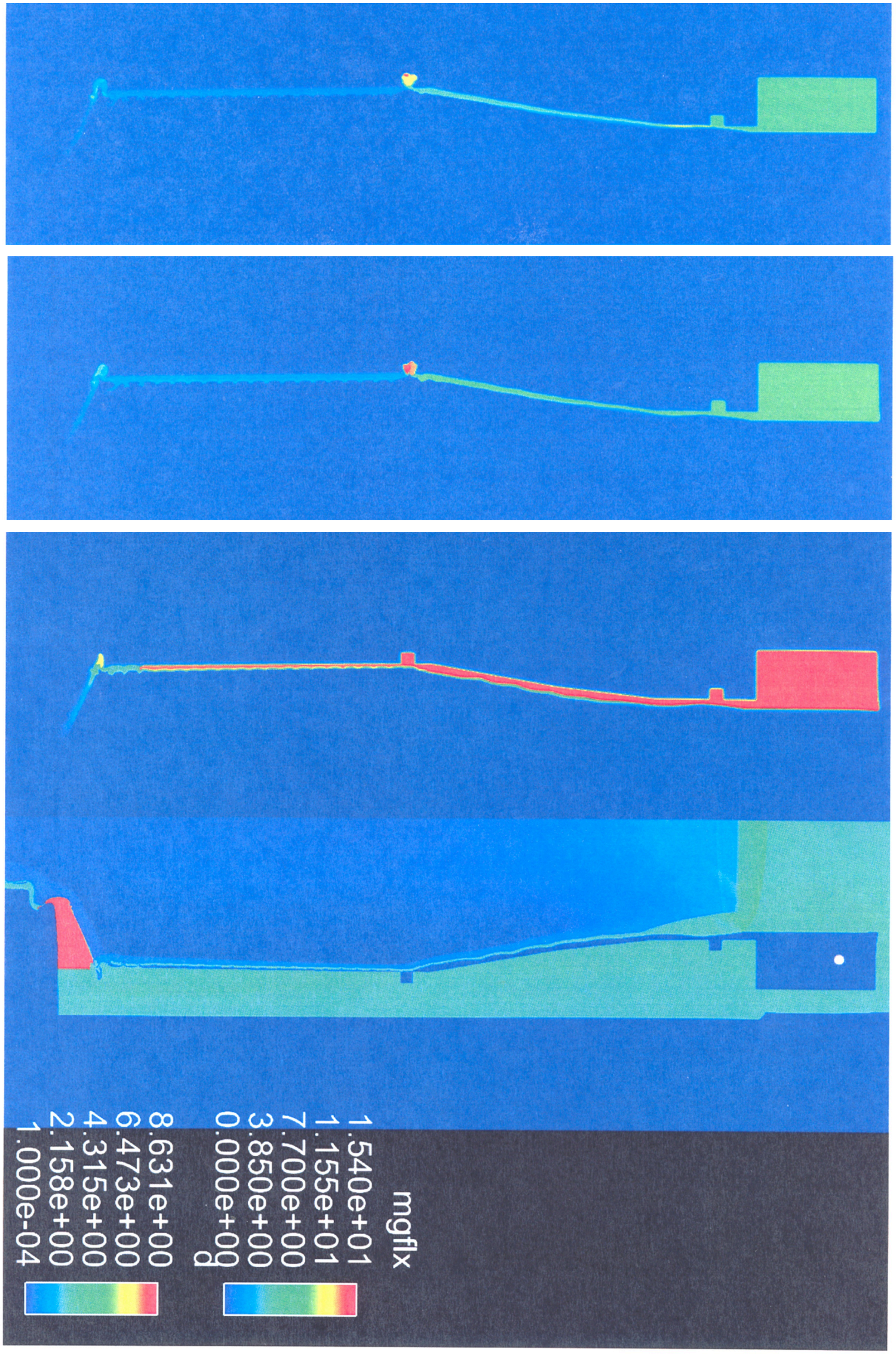
mgflx
1.540e+01
1.155e+01
7.700e+00
3.850e+00
0.000e+00
8.631e+00
6.473e+00
4.315e+00
2.158e+00
1.000e-04

Figure 8. The effect of high magnetic back pressure with a 10nH *static* load. The bottom part of the image is the normal density plot near peak current with a 12MA seed. The three images above are the flux plots at peak current for the 3.5MA (top), 8MA (middle), and 12MA (lower) seed current case. Note the open bell section with a 12MA seed current, with high flux all the way back to and including the straight section and the mid-system FR groove, which would normally crowbar the flux out of the straight section, separating the FCG and load into three separate regions (straight section, bell section, and load section), each with a separate flux level. This separation does not happen at 12MA due to magnetic back pressure above 50kbar which holds the bell section open near peak current. The effect is just beginning to occur in the 8MA seed case as well but is not as pronounced.

## System Energetics

The new generator was expected to have favorable energetics behavior, delivering a significant fraction of the armature kinetic energy into the magnetic flux and subsequently into an appropriate load. To examine the energetics, a simulation with the generator into a *static* 10nH load with a seed current of 8MA was analyzed. This seed level was near where the 10nH load flux compression efficiency rolls over so the transfer efficiency into the quasi-static load is probably close to as high as it can get. Figure 9 shows the energetics of this configuration. The overall transfer efficiency of the 29MJ armature kinetic energy into the total magnetic flux energy of 21.35MJ constitutes an overall efficiency of approximately 74%. The load contains about 87% of the total magnetic energy at 35us after first motion.

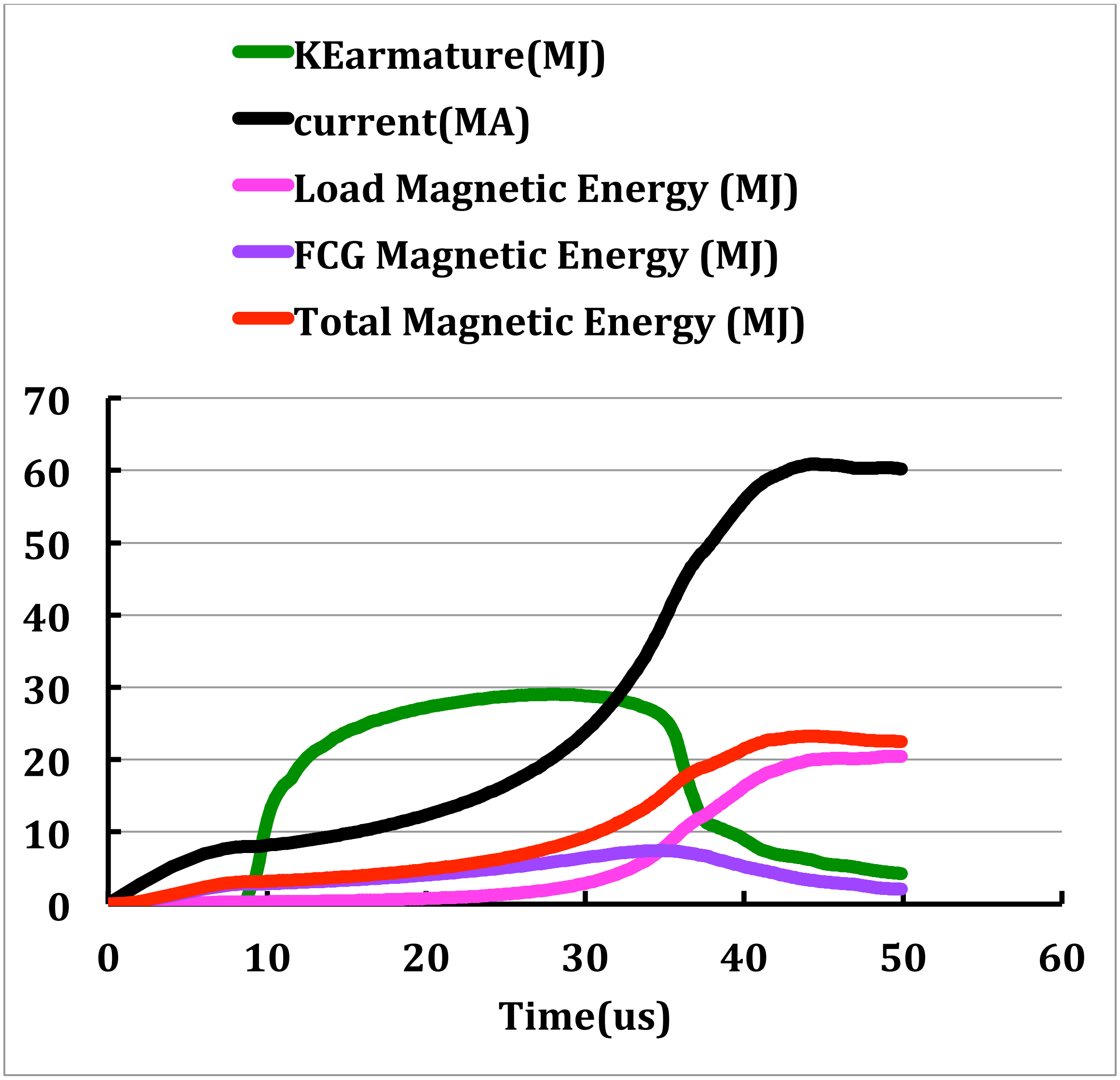


Figure 8. Energetics of LA43S driving a 10nH *static* load. The current history is shown in black. The armature kinetic energy is the green curve, which peaks at ~29MJ and the total magnetic energy is the red curve peaking at about 23MJ. The magnetic energy in the FCG void (purple) and in the load (magenta) are shown to show the partitioning.

## Conclusions

The new generator's design does not appear to suffer the same problem with an unpredictable peak current due to an aneurism, as may have been the case in the previous Ranchero design. It has an initial inductance about 55% larger than the earlier design and a consequent potential to better drive high inductance loads. The peak current seen using 3.5MA seed current with a 10nH load, 29.8MA, lies midway between the ideal 34MA peak of that system and the estimated peak of 24.5MA based on scaling losses from LA43-2. The simulated peak currents appear to exceed those that one might expect based on scaling of the losses from LA43-2 simply based on the increased perimeter of the SF6 cavity; hardly surprising since the earlier peak current is believed to have been significantly reduced due to a potential aneurism resulting in lost flux near the output glide plane. If one scales losses from that earlier work without accounting for the difference in the losses due to an aneurism, he would over-estimate the losses. Detailed examination of the magnetic pressure in the FCG void shows it exceeds 50kbar everywhere in the bell section at 70-80MA, which is sufficient to push back on the armature during the final closure of the bell section of the generator, and not allow the complete closure of that flux trap. This back pressure, applied for a longer time with a larger inductance load, appears to limit the ability of the generator to drive a 5-10nH load using the 10-12MA seed currents expected to be required to reach the 100MA range. (Because the code has no shorting model, flux can be pulled back from any section of the load not isolated from non-closed regions of the FCG main cavity, so the flux reduction due to armature stopping and bounce is probably over-estimated.) The implication is that to actually reach the 100MA range with the RancheroS type generator using 10-12MA seed currents will probably require the use of the 100cm version, rather than the 43cm version studied here. Again this is not a real surprise based on earlier examinations of the system with a 10nH *static* load and an approximation of the LA100S generator. It may also benefit the drive abilities of the new generator to increase the radius of the output transmission line, thus reducing the magnetic pressure at any peak output current level, and mitigating the effect on closure of the bell section so that higher currents can be achieved with less stoppage and bounce of the armature. Future work will study the drive capabilities of the present 100 and 144 cm designs of RancheroS.

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