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Author(s): J. H. Goforth
H. Oona
D. G. Tasker
R. G. Watt
C. L. Rousculp
W. L. Atchison

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Capabilities for High Explosive Pulsed Power Research at Los Alamos National Laboratory

J. H. Goforth, H. Oona, D. G. Tasker,
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Abstract

Research on topics requiring high magnetic fields and high currents have been pursued using high explosive pulsed power (HEPP) techniques since the 1950s at Los Alamos National Laboratory. We have developed many sophisticated HEPP systems through the years, and most of them depend on technology available from the nuclear weapons program. Through the 1980s and 1990s, our budgets would sustain parallel efforts in z-pinch research using both HEPP and capacitor banks. In recent years, many changes have occurred that are driven by concerns such as safety, security, and environment, as well as reduced budgets and downsizing of the National Nuclear Security Administration (NNSA) complex due to the end of the cold war era. In this paper, we review the techniques developed to date, and adaptations that are driven by changes in budgets and our changing complex. One new Ranchero-based solid liner z-pinch experimental design is also presented. Explosives that are cast to shape instead of being machined, and initiation systems that depend on arrays of slapper detonators are important new tools. Some materials that are seen as hazardous to the environment are avoided in designs. The process continues to allow a wide range of research however, and there are few, if any, experiments that we have done in the past that could not be perform today. The HEPP firing facility at Los Alamos continues to have a 2000 lb. high explosive limit, and our 2.4 MJ capacitor bank remains a mainstay of the effort. Modern diagnostic and data analysis capabilities allow fewer personnel to achieve better results, and in the broad sense we continue to have a robust capability.

Introduction

Los Alamos National Laboratory has a long history of magnetic flux compression (MFC) and HEPP work. This paper will review techniques and systems developed in the past. This sets the stage for discussion of the impact of reduced R&D funding, downsizing of the NNSA complex, and increased awareness of safety, security, and the environment. A few cases will be discussed in which new techniques are replacing methods that are no longer practical. Current HEPP efforts at Los Alamos are mentioned, and a description is given of a new system under development. Finally, we will summarize the existing capabilities that allow a complete range of HEPP work with affordable techniques that will continue to be available into the future.

Historical Review

Any historical review of Los Alamos HEPP should start with the work of Max Fowler, Bob Caird, and Wray Garn. From the mid 1950s, flux compression experiments were conducted for plasma and high magnetic field research. Flux compression tools at the time consisted of basic components such as commercial sheet explosive, simple machined high explosives (HE), detonators, and plane wave lenses. At that time these were used in large quantities throughout the lab, and were both inexpensive and readily available. In spite of their simplicity, Max's two-stage strip system would generate ~ 3 MG fields, as shown in figure 1. The onset of plasma radiation source (PRS) development in the early 1970s was one of the major driving forces leading to HEPP advances. The initial experiments were funded by the U. S. Air Force, and utilized parallel plate MFC generators (plate generators) with a "ballast load" to complete the circuit until the plasma z-pinch implosion load was switched into the circuit. In the first shot in 1974, ~26 MA were generated by three plate generators in parallel. Figure 2 shows that in this experiment, 18 MA was the peak current in the parallel "ballast" load, and only 8 MA went into the plasma z-pinch load. The load current rise time was ~3 μs. Los Alamos continued the development of HEPP driven PRS systems in the early 1980s, and opening switches for pulse compression became a priority. Every new system after 1982 had some type of opening switch as part of the circuit. The plasma z-pinch work culminated in 1994-1995 with the Procyon system, which produced 1.7 MJ of soft x-rays. The system used a MK-IX helical generator to produce ~16 MJ magnetic energy, and explosively formed fuse (EFF) opening switches that operated at ~2 TW for 3 μs. Plasma flow switches were also developed for Procyon, and these allowed 500 ns load current rise times. However, it was found that long time scale (~2 μs) implosions were adequately stable, and the best radiation producing tests used only EFFs for pulse compression. Figure 3 shows currents from three Procyon tests. The difference in load current between the 1974 and 1994 tests seems small. However, the Procyon load was ~30 nH in contrast to only a few nH for the 1974 experiments. This increase was due, in part, to the opening switch transmission line inductance and in part to radiation baffling necessary to prevent restrike of the vacuum dielectric interface. That interface failed in the 1974 test, and solutions were found subsequently by the Air Force Research

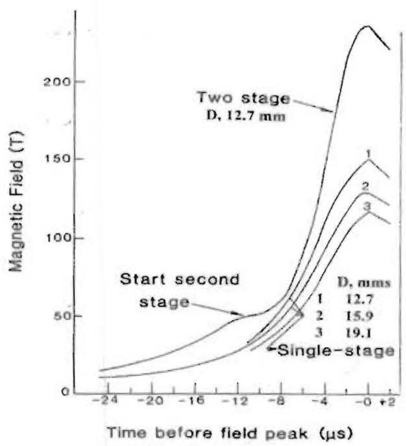

Figure 1. Magnetic fields generated using Max Fowler's one and two stage strip generator systems.

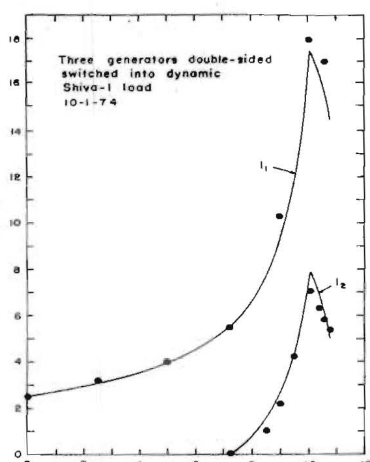

Figure 2. Currents in 1974 plasma radiation source experiment. I_1 (peak ~18 MA) is the ballast load current and I_2 (peak ~ 8 MA) is the load current. There was no opening switch in this experiment.

Laboratory Shiva program. The solution came at the price of higher inductance transmission lines. The pulse compression scheme that allowed the 16 MJ store to be tapped and the radiation baffling that allowed the transmission lines to remain open while energy flowed to the load from the store, are the major accomplishments of the 20 year period. The radiation baffling techniques were pioneered by the Shiva program and adapted to Procyon. There were many HEPP developments at Los Alamos between 1982 and 1994. Generator developments included plate generator optimization, the MK-IX generator, and sweeping wave coaxial generators. Opening switch developments included plasma compression opening switches, EFF opening switches, and plasma flow opening switches. There were also several closing switches investigated, and cylindrical detonation systems became operational. In addition, in the early 1990s, Bruce Freeman and others developed the CN-III simultaneous coaxial generator, which delivered 160 MA to a 2 nH load. By 1995, we depended on a full range of sophisticated HE techniques, many of which were borrowed from the nuclear weapons program. From 1996 to 1999, the Ranchero simultaneous coaxial generator was developed for solid liner z-pinch experiments. During development phases, we demonstrated that Ranchero generators would produce over 50 MA. Ranchero used slapper line detonators developed in the early 1980s combined with cast-to-shape explosives for cost effectiveness. Liner tests performed in 1999 were in support of the Atlas program, and 18 MA was delivered to a solid liner to demonstrate a particular insulator design and methods for diagnosing it. All diagnostics functioned properly on the test, and the insulator proved adequate. The test also indicated that liners could become unstable in this drive scenario. The experiments above are all described in papers that can be found in this Megagauss conference series or in the IEEE Pulsed Power Conferences, and show a progression of systems designed for powering ever larger z-pinch experiments. For a time, budgets were robust enough to support parallel capacitor bank powered research as well. During the period when HEPP experiments were using the Laguna and Procyon systems, Los Alamos built and conducted tests with the Pegasus capacitor bank. This allowed research on load physics topics at an increased shot rate. Both plasma z-pinch and solid liner z-pinch work were performed on Pegasus, and its success helped justify the Atlas capacitor bank, which was under construction during the Procyon HEPP experimental program. It was a major factor in justifying Ranchero development. Ranchero generators could perform implosion experiments to pave the way for Atlas work, and then go on to energy levels beyond.

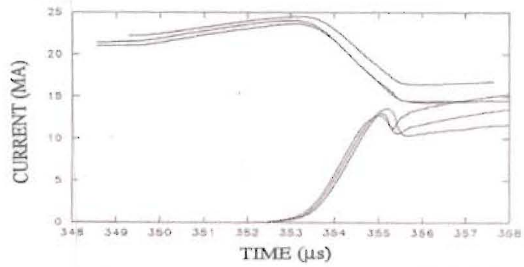

Figure 3. Currents from 3 Procyon PRS experiments. The upper curves (20-25 MA) are currents in the ~72 nH storage inductor, and the lower curves (13-15 MA) are load currents.

Reduced R&D Budgets

Diminishing budgets at the end of the cold war, however, gave way to cutbacks in these parallel efforts. Procyon successes in producing soft x-rays in 1994 and 1995 were well documented. With the Sandia z-machine to be operating by ~1996 for PRS work, and

Atlas intended for solid liner research, Los Alamos abandoned plasma radiation source development. Ranchero work was subsequently terminated so that remaining funds could be applied to finishing Atlas and performing experiments. Operating expenses were large compared to further diminishing budgets, and it has now been mothballed. As a result, the Ranchero system has again become an attractive choice for work requiring tens of MA current. Individual shot costs are somewhat higher for the explosive system, but operating costs are relatively small.

Downsizing the NNSA Complex

In further response to the end of the cold war, the NNSA is implementing a move to downsize the entire complex. Initial recommendations to "downsize in place," meaning reduce the level of effort at each site but leave each with most of its original capability, have been abandoned. A "centers of excellence" model is now favored. In this model, each site maintains major capabilities, but gives up the ability to perform all of the tasks that it previously could. Many details of this plan are being reconsidered, but some of the impacts are already being felt. As an example, Los Alamos HE manufacturing capability has been substantially reduced. We maintain the ability to make modest size HE charges, but we have given up the ability to make larger ones. Our plate generator explosives charges (~50cm X 13cm X 2.5cm), for instance, will have to be made in 2 or 4 pieces in the future, instead of a single slab. These pieces can be glued together effectively, but it will require extra labor. In addition to downsizing, there is a reduced number of experiments being conducted by the nuclear weapons programs at Los Alamos. This has a different impact on R&D programs using explosives. Whereas in the past our facilities were fully supported by the weapons program to meet the cold war needs, R&D programs must now pay a significant share of the support when they use them. This increases costs. Further, we have considerably reduced our staff at these facilities, and many personnel with specific knowledge of weapons techniques have retired and not been replaced. We still know the design principles, but many personnel with "hands-on" experience are gone, and reproducing old hardware will, in some cases, require re-development. Finally, because there is a much reduced level of effort in HE experimentation, commercial vendors must also cover their overhead with the sale of fewer items. Thus, again, the prices on items that were once negligible are now significant. Standard detonators and detonator cables, for instance, are now a significant fraction of the cost of experiments. In summary, the end of the cold was has led to a reduced level of effort in weapons program work. In combination with downsizing initiatives, this leaves us with a reduced staff of people who know the complete range of techniques, reduced on-site manufacturing capability, increased requirement to cover facility overhead from our programs, and the price increases incurred from using low-volume hardware. In response to these factors, we are pursuing new techniques for HEPP devices in many cases.

Cost Effective Replacements

As a natural consequence of trying to keep the cost of HEPP experiments competitive, for over a decade we have been working on new techniques that offer relief. Ranchero development led the way in this effort, and a different approach that is both cost effective and flexible for many special detonation system needs has been developed. Both linear and area arrays of slapper detonators, with cast to shape HE to replace very expensive machined parts, can now be fielded. The initiation systems used in the CN-III, the Procyon EFF, and plate generators can now be replaced with slapper arrays. The Procyon EFF is a good example of the difference. For that assembly, eight cylinders of HE were pressed and machined to size, glued together to make two long cylinders, and then machined into two perfect half cylinders. Each of those was grooved for a slapper cable, and a counter bore for each slapper pellet was made in the bottom of the groove. The slapper cable was carefully position, sealed, and the two halves glued together for assembly into a machined main HE charge. At the present time, we replace this technique by stretching slapper cables down the center of an armature or opening switch tube with slapper pellets attached. The main charge HE is then cast around the slappers and pellets, and once cured, the part is ready to use without machining. These charges have been made up to 1.4 m in length for Ranchero, and there is no limit on diameter that would affect HEPP work. In scaling costs from the early 1990s to today's costs and comparing the Procyon charge to Ranchero, we save a factor of more than ten in the cost of each.

Cost savings can be realized in other areas as well. Los Alamos has replaced carefully machined plane wave lenses with equally carefully pressed-to-shape lenses. For reasons cited, the increase in cost of plane wave lenses was approaching a factor of five. The new lenses currently cost approximately what they did five years ago in spite of inflation. Further, as was shown in an earlier paper,[1] machined PBX-9501 charges in copper armatures can be replaced by cast PBXN-110 charges in aluminum armatures, with a net improvement in performance and a major savings in cost. Finally, we are now considering the use of standard coaxial cables and connectors to replace very expensive ones designed especially for detonators. Existing special detonator cables and connectors have an inherent safety advantage, since they can only be connected to detonator circuits. However, with careful planning we can overcome the safety issue, and realize major savings by adopting more standard hardware. We also have a long history of excellence in manufacturing detonators of the highest quality. However, in some cases, such high quality units are not required, and we will no doubt resort to using less expensive commercial detonators where they are acceptable. Slappers offer advantages here, as well, since we can use low-cost commercial initiator pellets with slappers, and there is no high precision pressing required. Each new slapper system requires some development cost, but once proved, slappers can be inexpensive.

Security, Safety, and Environment

In general, new initiatives related to environment, safety, and security have multiple impacts. One trend is toward increased staff for surety organizations, leaving fewer personnel directly performing research. Researchers also must devote a larger fraction of their time to surety issues. One clear example relates to safety. Los Alamos is currently following an approach that maintains our long term practice of performing tasks safely by having qualified individuals perform the work. Modern standards, however, require more documentation of the processes, and more rigor in assuring that the process has been followed. Other examples relate to the environment. Some practices, once believed to be harmless, or at least acceptable in light of the need for our research, are now considered unacceptable. A good example is the use of lead in experiments. In earlier decades, it was common practice to use lead as a cheap and efficient material for providing inertial confinement for experiments, which frequently suffer from the high magnetic pressures generated. Our sweeping wave coaxial generator, for instance, used a spun-formed copper stator that was inexpensive to build in a complicated shape. The stator, however, needed to be thin enough to form onto a mandrel for the process to work. To provide extra mass inexpensively, a sheet of lead was wrapped on the outside of the stator. This technique could not be justified in the modern environment, and a substantially more expensive, lead free, manufacturing technique would have to be used. Another environmental example is the use of tritium in experiments. The joint Los Alamos/VNIIEF MAGO experiments in 1994 used a 100 Curies of tritium which was automatically permitted then. At this time, it would most likely be possible to perform the same test, but a special permit would have to be obtained. The major impact is the pace of the experiment and to do those tests, we would have to propose them, file for a permit, and then wait for the permit in order to proceed. This takes time, and in some cases discourages experiments from being proposed. Fire is another issue that is treated with more care than previously at explosives firing sites in Los Alamos. As many know, in the spring of 2000 after an extended drought, a fire started in the forest near Los Alamos and ultimately destroyed approximately 400 homes and some structures at the lab. There are signs that our drought may be lifting, but Los Alamos has become very cautious about starting fires during explosives events. There is now a monitoring service that provides data on fire propagation conditions, and this information is given to laboratory experts. They then include critical parameters of the particular experiment and depending on other factors such as wind speed and shrapnel, allow or deny permission to fire a shot.. In some cases, extensive mitigation steps are taken to assure with high confidence that a fire will not be started. This increases the likelihood that we can conduct the experiment at the time of our choice, but it adds effort and cost to shots where it is required. The integrated impact of all of these concerns is to slow HE related research and increase the cost.

Current Programs

HEPP research continues at Los Alamos. In this conference, there is a paper by Tasker[2] reporting progress on HEPP driven isentropic compression experiments and a paper by Oona[3] describing some of the on-going Ranchero development work. In addition, there is a new program beginning that will use Ranchero generators for imploding solid liners. For these experiments, we will use a 1.0 m long Ranchero generator and small EFF opening switches to carry current during the first 66 μs to prevent early magnetic pressure from distorting the load. A new 1 m detonator is currently being developed. Figure 4 shows calculations of the basic performance of the system. The capacitor bank current peaks at ~4 MA and 66 μs. At that time the armature begins to move in the Ranchero generator. In this design we are including a layer of insulation between the output glide plane and the armature. The circuit is completed via postholes that connect the armature to the outer transmission line through EFF opening switches. When the armature starts to move, it shorts the insulation at the glide plane and current can flow out the glide plane to the load. At this time, the EFFs are actuated and the parallel path through the EFFs becomes relatively high impedance. Current quickly dies in that leg as flux transfer occurs to the load circuit, and all the current amplification due to flux compression is delivered to the liner load. The peak liner current is expected to be ~40 MA, as show in the figure. A cross section of the system is shown in fig. 5. The EFFs in this circuit will have to dissipate ~160 kJ, which can easily be done by four parallel switches that are 6.35 cm wide and have an active length of 7.4 cm. These switches have been shown to interrupt 1 MA in experiments in the past, and so four of them will suffice for this system. One preliminary experiment will be conducted to test the EFF switches, the post hole connections, the glide plane closing switch, and current joints that will be required to operate at 40 MA on actual liner experiments. We had three 1.4 m long armatures left over from previous Ranchero work, and one of these was recently tested to see if it still functioned properly. It did, and we will use one of the remaining armatures for this preliminary test. This will allow us to proceed with testing while we finish the development of our new 1 m detonator.

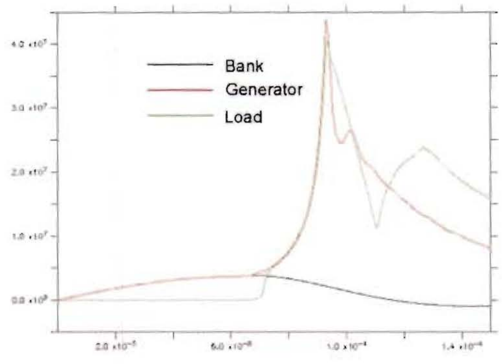

Figure 4. Currents calculated for a new Ranchero powered liner experiment. Black is the bank current, red the generator current and green the liner current.

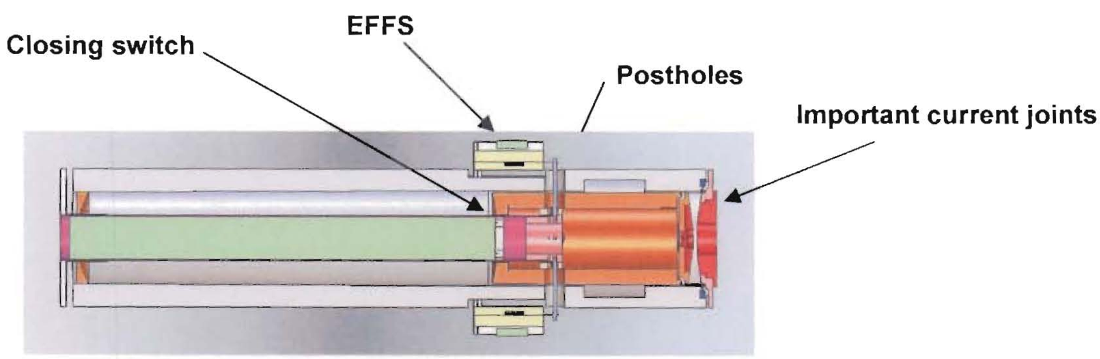

Figure 5. Cross section of a new Ranchero system. The glide plane closing switch, EFF opening switches and postholes, and current joints shown are all important features of the new configuration that will be tested using a 1.4 m long armature available from past experiments

Capabilities and Conclusions

In spite of the many changes at Los Alamos, we retain a full range of capabilities. A complete complement of diagnostics exists that can be used at our facilities at any time. These include Faraday rotation current measuring systems, VISAR and PDV systems, a range of x-rays from 150 kV to 1 MV, both electronic and rotating mirror cameras, and a good complement of digital recording instruments. Our 2.4 MJ bank remains one of the mainstays of our operation, and we have a bay that houses mobile recording trailers when extra data channels are needed. Computer codes continue to improve, allowing us to get to the final result with fewer iterations than in the past, and this fact and our digital instrumentation allow fewer people to produce more work. At the end of Max Fowler's first 30 years of HEPP research, our firing bunker housed a 1.5 mF 20 kV capacitor bank, we could fire 250 kG HE, and we had 20 or 30 oscilloscopes for recording data. Today, we can fire 1000 kG HE, at a bunker with a 12 mF 20 kV capacitor bank, with 100 permanent digital recording channels. To conclude, we have a first rate facility in which to work, cost effective HE techniques to replace outmoded ones, and the charter to do HEPP experiments. The reduced pace of our work is somewhat offset by improved computing capabilities and the advantages provided by digital data acquisition systems and the accompanying improved speed and accuracy of data analysis.

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