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MC-1 GENERATOR PERFORMANCE WITH HIGHER-ENERGY EXPLOSIVES*

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The Russian designed MC-1 ultrahigh magnetic field generator was tested in 5 experiments as part of a joint US-Russian collaboration at Los Alamos National Laboratory in December of 1993. The standard Russian explosive (50/50 RDX/TNT) was replaced with higher-energy-density US explosive, either Comp-B (60/40 RDX/TNT) or PBX-9501. Generator performance with COMP-B was nominally the same as reported for experiments with the slightly lower-energy Russian explosive. The Comp-B experiment produced a measured peak field of 9.4 megagauss. Using PBX-9501, the measured peak field increased to 10.9 megagauss with an appropriate increase in the time derivative of the field. One-dimensional MHD calculations with the Lagrangian code, RAVEN are compared with the experimental results.

I. History and Background

The reliable and reproducible generation of multi-megagauss magnetic fields using high-explosive flux-compression techniques has been of continuing interest to two research groups for over 30 years - one led by C. M. Fowler at Los Alamos National Laboratory in the U.S., the other led by the late A. I. Pavlovskii at Arzamas-16 in Russia. In 1991, with the reduction of political and military tensions between our two countries, these two groups initiated a collaboration to generate and use ultrahigh magnetic fields.

The first series of experiments in this collaboration was conducted by U.S. and Russian scientists at Los Alamos in December of 1993 using the Russian MC-1 flux-compression generator (FCG)[1], U.S. high-explosives, and diagnostics fielded by both countries. The four goals of the five-shot series were accomplished. The goals were:

1. validate MC-1 performance and 10 MG peak field with Comp-B high-explosive (shot #1),
2. make direct A-B comparison with a higher energy density explosive, PBX-9501, and benchmark computational models (shot #2),
3. measure the upper critical field transition, $H_{c2}(T)$, of the high temperature superconductor $YBa_2Cu_3O_7$ down to 4 K and measure the nonlinear Faraday effect in CdS (shots #3-5), and
4. continue building the foundation for a joint program to generate 20 MG fields.

Results of the December 1993 experiments relevant to MC-1 performance are presented below. Results of the high-field measurements for $YBa_2Cu_3O_7$ and CdS are published

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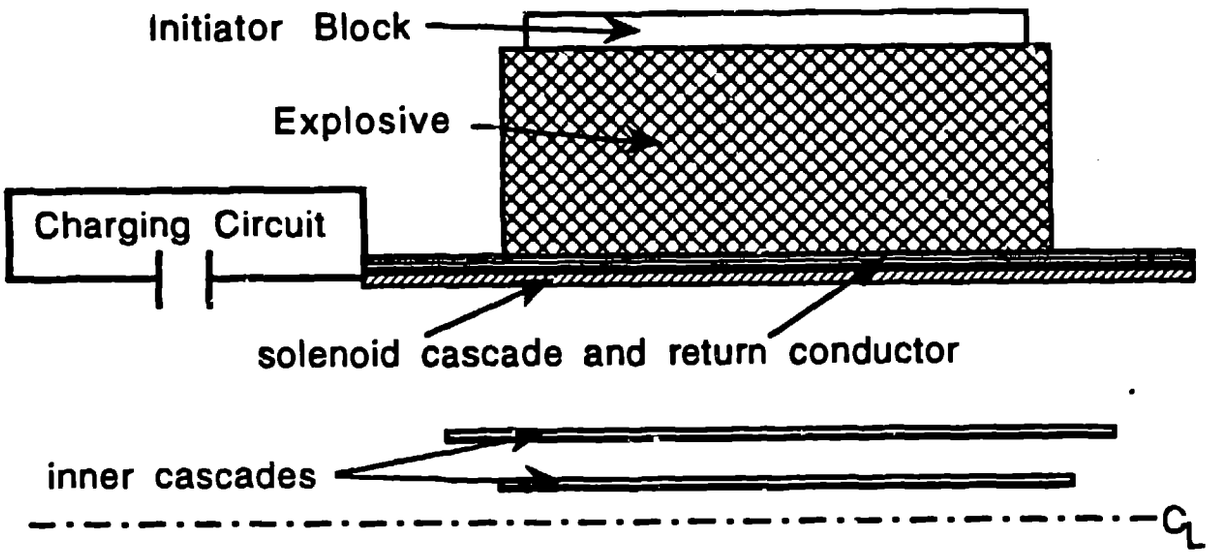

Fig. 1. Diagram of the Russian three-cascade MC-1 FCG.

elsewhere.[2] Section II describes the MC-1, its operation, and the experimental setup. Section III describes the 1D MHD calculational models employed in the RAVEN simulations. MC-1 performance is compared with the RAVEN simulations in section IV; and section V reviews conclusions of the series.

II. MC-1 Description and Operation

A diagram of the Russian three-cascade MC-1 FCG is presented in Fig. 1. The HE cylinder, which in previous Russian experiments consisted of a 50/50 RDX/TNT mix, is detonated simultaneously on its outer diameter surface by a ring of 10 polystyrene block initiators. For this collaboration, the HE was replaced with higher energy explosives — either Comp-B, a 60/40 RDX/TNT mix, or PBX-9501. Inside the HE are 3 concentric cylindrical shells made of a unique copper-epoxy composite. These shells, known as cascades in the Russian literature, successively take on the role of armature during implosion. The shells are made of hundreds of 0.25-mm diameter, enamel-coated, copper threads, arranged side-by-side in layers, secured in a casting of epoxy. The 500 copper threads of the outer cascade are wound in a 2-turn solenoid and then brought back along the outside diameter, parallel with the cylindrical axis, to complete the return current path. The outer diameters of all 3 cascades are cast with a thicker layer of epoxy so that they can be machined smooth to inhibit hydrodynamic instabilities. An initial magnetic field of up to 220 kG (160 kG for these experiments) is created by discharging a capacitor through the first cascade. The discharge is timed so that peak field is achieved just as the HE detonation wave reaches the first cascade. The HE shock breaks down the insulation between the solenoid threads and transforms the first cascade into a conducting cylinder — trapping and then compressing the initial field as the shell begins to move.

The second and third cascades are similarly constructed except that all of the copper threads are laid parallel to the axis. Before a cascade is shocked from outside, it will only conduct current in the axial direction. Hence, it is transparent to the axial field which is being compressed by the preceding shell. On contact with the outer shell, the next cascade is transformed by the shock into a conducting cylinder, which traps the field inside as the new cascade becomes the new armature.

The use of multiple cascades serves two important functions. The first benefit of multiple cascades is the velocity enhancement which is derived from collisions of heavy outer shells with lighter inner shells. The second (and more crucial) benefit is related to implosion stability. As the outer cascade compresses flux, magnetic and hydrodynamic instabilities tend to disrupt the shell. These instabilities are made worse by the inherent perturbations associated with the copper-epoxy composite. The inner cascades are strategically placed to re-collect and smooth out the perturbations before the outer cascade is disrupted. The loss of flux which is incurred during the transition is off set by achieving a more stable and reproducible implosion.

In the early systems developed by Fowler, Garn and Caird,[3] initial field coils were also placed under the explosive charge. While very large fields were obtained (up to 14 MG), performance was erratic. The use of additional Pavlovskii cascades would presumably have led to better reproducibility, albeit somewhat lower peak fields. An alternative approach to controlling the instabilities was investigated by Caird et. al.[4,5] They placed the solenoid outside of the HE and used a single stainless steel armature. On the timescales of the initial capacitor discharge, the stainless steel armature allowed magnetic flux to diffuse inside the cylinder; but on the short timescale of the implosion, the flux was essentially trapped and compressed. However, the poorer coupling of the initial coils with the armature results in substantially lower initial, and therefore, also final compressed fields.

The first test in this series was a proof test of the 3-cascade MC-1 generator using Comp-B HE instead of the Russian 50/50 mix. The generator was preloaded to 160 kG using the capacitor bank at Point 88 in Ancho Canyon. Time-dependent field measurements were made with multiple inductive probes (dB/dt loops) located at different radii and of different sensitivities; and with Faraday crystal(s) as close to the axis as possible. The second experiment of this series was an identical test of the 3-cascade system using PBX-9501, a dramatically higher energy HE. Results of these tests are compared with preshot and postshot calculations described in the next section. Benchmarking of the RAVEN code at these high fields is one step towards pursuing the 20 MG goal.

In the HTSC experiments, described elsewhere,[2] the third cascade was removed, and the volume inside the second cascade was occupied by a 0.15 g/cm^3 foam cryostat. The CdS and superconducting samples were placed near the center of the cryostat where they were exposed to ultrahigh fields while their responses were measured.

III. Computational Models

Simulations of the MC-1 have been conducted with the 1D Lagrangian MHD RAVEN code. Cascades were modeled either as a homogeneous composite of the correct average density using a mixed Cu/epoxy equation-of-state (EOS), or as sandwiched layers of copper and epoxy using the same unmixed EOSs employed in the mixing procedure.[6] The number of layers used for each cascade matches the actual number of layers of copper thread in each cascade and the thickness of the layers was adjusted to match the reported average density of each cascade while fixing the total sandwich thickness. This mixed EOS model is similar to earlier Russian computational models,[7] which used a different mixing algorithm. As in earlier Russian calculations, we used a standard copper resistivity model[8,9] scaled by a factor of 5 for the mixed EOS. To allow the axial magnetic field to pass freely through the cascades until they were shocked in the calculations, the resistivity in each cascade zone was multiplied by a step function which remained zero until the zone density first exceeded 1% above normal density; the step function stayed equal to one for the remainder of the simulation. The HE was modeled with a JWL form scaled to give experimentally measured cascade velocities.[6] HE detonation in RAVEN is modeled as a programmed burn with a specified detonation velocity.

IV. Comparison of Results

Cascade radii as functions of time for Comp-B simulations using the mixed EOS are shown in Fig. 2a; similar PBX-9501 simulations are shown in Fig. 3a. Calculated turn-around for the inner cascade is 4.0 mm for Comp-B and 3.5 mm for PBX-9501. Cascade velocities from these

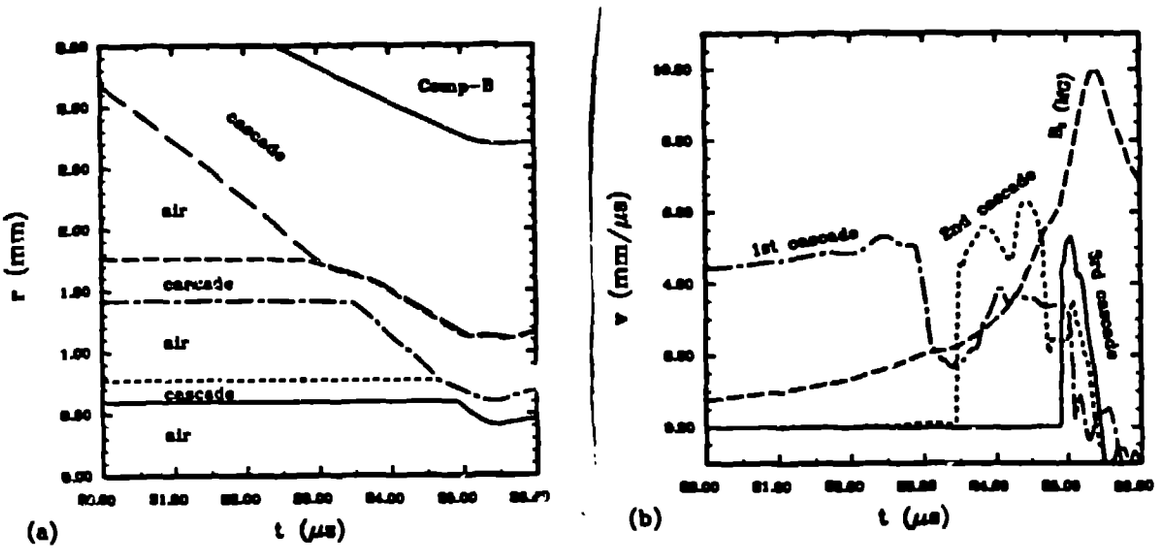

Fig. 2. Cascade radii (a) and velocity (b) for Comp-B simulations using the mixed EOS. Calculated field is overlaid in (b).

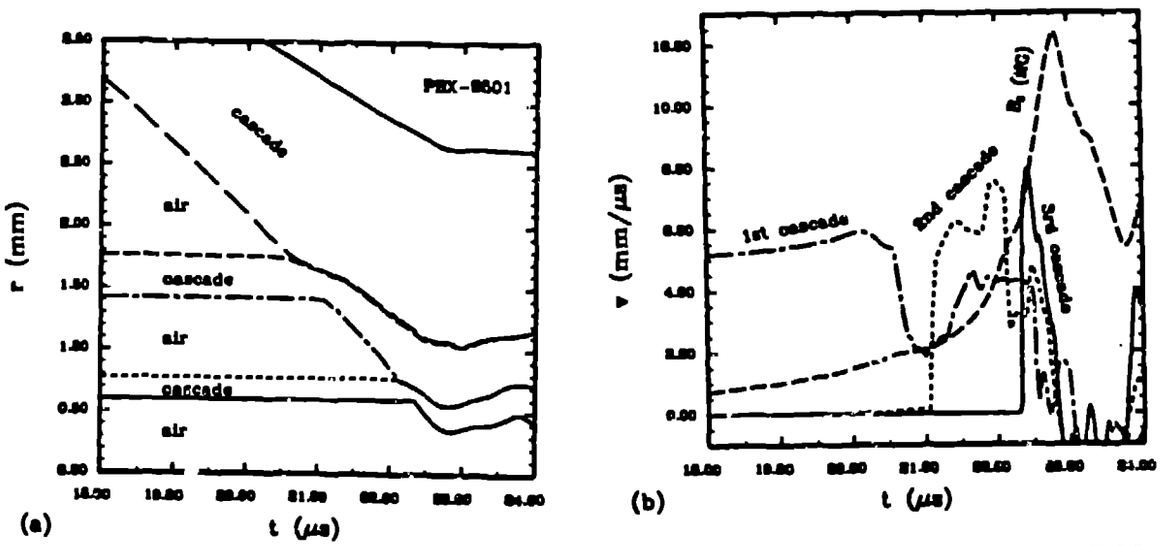

Fig. 3. Cascade radii (a) and velocity (b) for PBX-9501 simulations using the mixed EOS. Calculated field (MG) is overlaid in (b).

simulations are shown in Figs. 2b and 3b with calculated fields overlaid. Energy release in the HE model was adjusted to match the experimental cascade collision times as closely as possible for both experiments. The dips in the experimental and theoretical field derivative traces serve as unambiguous signals of cascade collisions. Since cascade kinetic energy is converted to magnetic field energy, matching the timing and hence the velocities is an important step in simulating the MC-1. Calculations with the layered model for cascades proved more difficult to adjust by scaling only the HE energy release. The main problem stems from shock reflections between the layers which delay the onset of cascade motion and alter the ultimate cascade velocity following collision. From the dynamics, it is clear that a homogeneous mixed EOS of the right average density is a better 1D model of the cascades than a layered representation of the correct mass.

Figure 4a shows the magnetic field trace for the Comp-B experiment compared with simulations using both the layered and the mixed EOS models. Measured peak field for the Comp-B experiment was 9.4 MG. Similar curves are shown for the PBX-9501 version of the

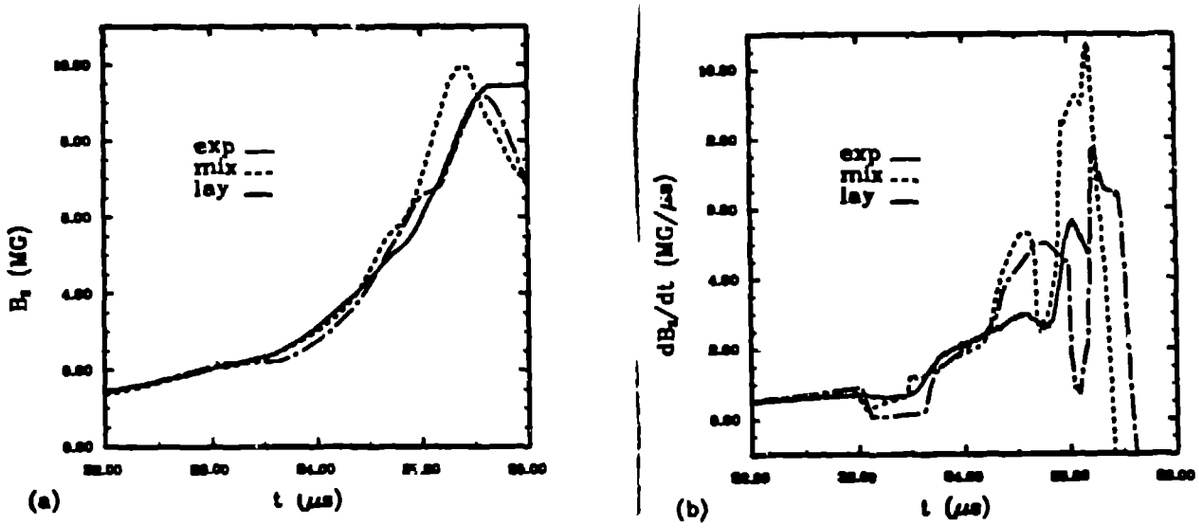

Fig. 4. Calculated field (MG) (a) and field derivative (MG/μs) (b) for Comp-B using the mixed EOS and layered model for cascades compared to experimental data.

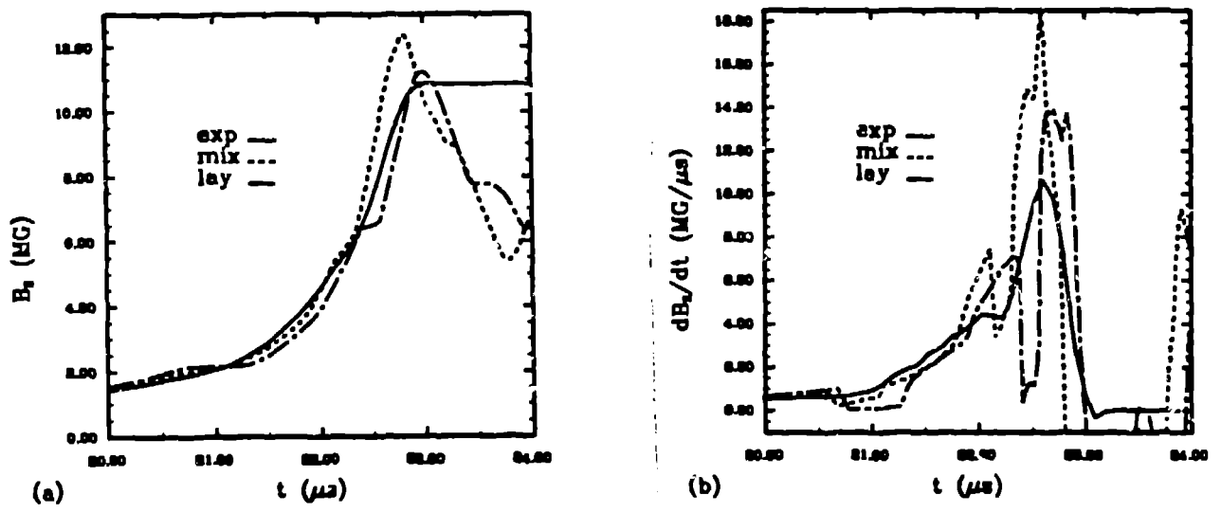

Fig. 5. Calculated field (MG) (a) and field derivative (MG/μs) (b) for PBX-9501 using the mixed EOS and layered model for cascades compared to experimental data.

MC-1 in Fig. 5a with a measured peak field of 10.9 MG. Corresponding field derivative curves are displayed in Figs. 4b and 5b. Notice that the mixed EOS model matches the timing for the cascade collisions better, even though the calculated peak field is matched better by the layered calculations. As discussed below, we believe that the layered calculations match the peak field better for the wrong reason. Also notice that the calculated derivatives are significantly higher than experiment just before cascade collisions and just before peak field.

V. Conclusions

Both simulations and experiments verify that the higher energy explosive produces a higher peak field. However, the higher field comes at the expense of a smaller turn-around radius. Another way to compare the data is to look at field vs. radius of the active cascade. Unfortunately, these curves only deviate at very high fields after the third cascade becomes active. Experimental data is neither temporally nor spatially resolved well enough to help at this

time, even if the inside radius of the cascade were well enough defined to make such a measurement meaningful. In the absence of data, we can only compare the fields from simulations for the two different explosives. At a radius of 4.0 mm the Comp-B simulation gives 10.0 MG and the PBX-9501 gives 10.9 MG. Since both simulations started with the same 160 kG initial field, we conclude that the MC-1 driven by the higher energy explosive allows less flux loss because the compression time is shorter. This happens even though the higher shock strength heats the cascades more resulting in a higher resistivity. Extrapolating this observation to real experiments however, is only conjecture.

Disagreement between measured and simulated time derivatives of the field, just before cascade collisions and just before peak field point to deficiencies in the one-dimensional nature of the simulations. Years of Russian experiments contributed to the empirical choice of inner cascade radii such that an unstable and spent outer cascade would be re-collected just before it disintegrated and lost too much of its compressed field. In the 1D simulations, cascades do not go unstable, electrical conductivities of the composite cascade materials are uncertain; and the modeling of the collisional turn-on of electrical conduction in the cascades is ad hoc. Given these caveats, the magnitude of the disagreement is surprisingly small.

As noted earlier, the better agreement between the experimental peak fields and the layered simulations is fortuitous. Because of the caveats explained above, the one-dimensional model underestimates flux loss during cascade collisions and at turn-around. Since the layered simulations dissipate too much energy in cascade collisions, they have an anomalously low kinetic energy which is available to be converted into magnetic field energy. This underestimation is offset by an anomalously low flux loss, therefore introducing a cancellation of errors that gives the right answer for the wrong reason.

Finally, one-dimensional MHD simulations of the MC-1 with Comp-B and with PBX-9501 are in good agreement with the data collected from joint experiments performed by US and Russian scientists in December of 1993. Information gained in this collaboration provides a foundation upon which additional ultrahigh field experiments can be conducted in the future. The detailed measurements and simulations associated with the collaboration also provide excellent benchmarks for investigations at even higher fields.

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