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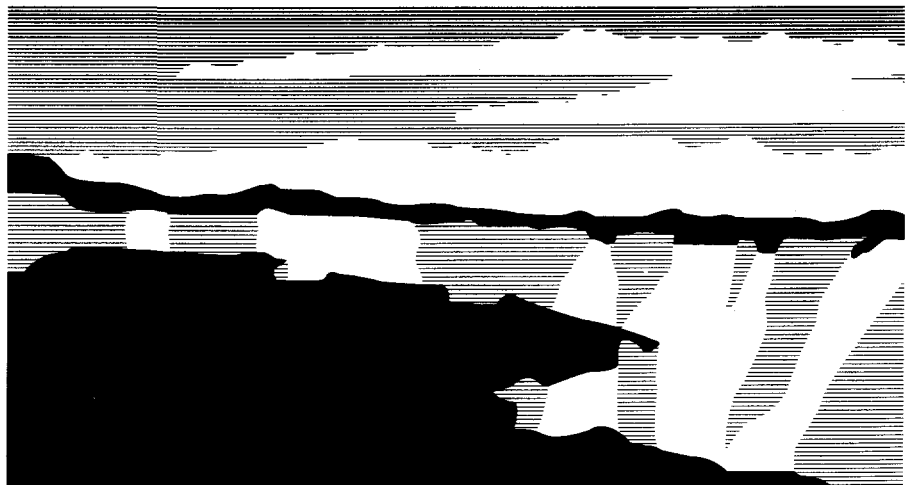
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THE RUSSIAN-AMERICAN HIGH MAGNETIC FIELD COLLABORATION*

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ABSTRACT

We report here on a joint experimental shot series with teams from Russia and the United States. The program was based largely upon the MC-1 generator, a high magnetic field explosive flux compressor, developed by the Pavlovskii group at Arzamas-16. The series was of historical interest in that it was carried out in a Los Alamos security area, the first time for such a collaboration. We discuss a number of technical issues involved in matching Russian hardware with Los Alamos explosives, initiation systems and the seed field energy source, as well as comparison of field measuring diagnostics furnished by the two teams. We conclude with a discussion of an investigation of the high temperature superconductor $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO), employing these generators. The low temperature critical magnetic field of this material was found to be 340 ± 40 T, as determined from a 94 GHz microwave interferometer developed for this purpose.

INTRODUCTION

In this paper, we give an overview of an experimental shot series carried out jointly by Russian and American scientists at Los Alamos's Ancho Canyon Site. This is a Security Site and, to our knowledge, this exercise was the first of its kind carried out at Los Alamos.

The program was mainly built around the MC-1 high magnetic field generator developed by Pavlovskii et al.¹ although some Los Alamos systems were also employed. In view of space limitations, we confine our attention here to the MC-1 generator and its applications. However, for the interested reader a much more comprehensive report of the program is now available.²

The MC-1 generator is described in Section 2, which also includes results from a preliminary test that established the compatibility of Los Alamos explosive fabrication and firing techniques with Russian hardware. Results from complete flux compression tests with two different types of explosives are given in Section 3, that includes a discussion of the field measuring diagnostics. Section 4 concludes the paper, and is devoted to the experiments used to find the upper critical field of the high temperature superconductor, YBCO.

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THE MC-1 GENERATOR

Figure 1 is a sketch of the complete assembly. Item 2 is the main explosive charge, with an outer diameter of 300 mm. Ten initiator blocks, each subtending 36° , are secured to the outer diameter of the main charge. The ten detonators, one for each block, in Russia are connected in series and fired simultaneously using a 60 kV x unit. At Los Alamos, detonators in this configuration are normally connected in parallel and fired with a 2500 V x unit.

Major generator hardware components are also shown in Fig. 1. A number of these are support and centering components as noted in the figure caption. The key components, items 10, 6 and 5, are called "cascades." The first cascade, #10, does double duty. It consists of hundreds of turns of fine, insulated copper wire. Each turn is first connected to the ring electrode "a", then wound over the cascade length as a 2-turn helix, and then returned parallel to the coil axis, outside of the helical winding, to ring electrode "b". The entire assembly is then potted in epoxy. This cascade first functions as the seed source for the generator, when current is passed through the solenoid. Its second role is that of a flux trapper during explosive compression. It does this when the explosive detonation front reaches the closely spaced, but insulated, copper wires. Shortly thereafter, the wires get fused together, thus forming a closed copper cylinder.

The second and third cascades, items 6 and 5, consist of a large number of fine insulated copper wires, aligned parallel to the cylinder axis and potted in epoxy. Magnetic fields pass freely through the cascades until they are hit by another, incoming cascade. Like the first cas-

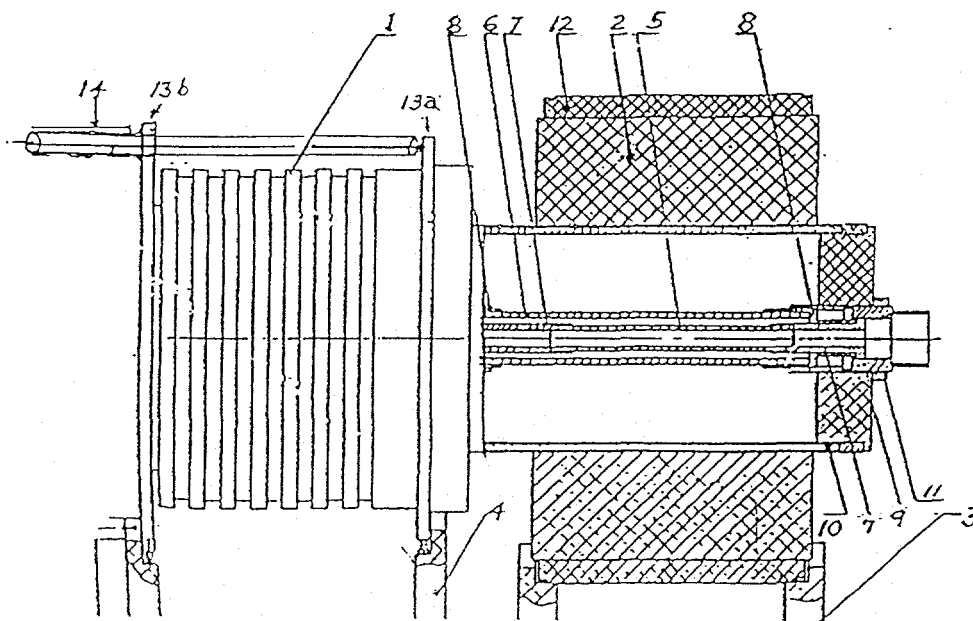


Figure 1. MC- I generator with three cascades. 1 -insulated current feed for solenoid, 2-explosive charge, 3,4- support stands, 5-third cascade, 6-second cascade, 7,8,9- support cradles for cascades, 10-solenoid (first cascade), 11 -assembly nut, 12-initiator block, 13a,b-ring electrodes.. The solenoid wires are connected to 13a, the return wires, parallel to the cylinder axis, are connected to 13b. 14-one of the coaxial cables (usually twenty- four) connecting the capacitor bank to the solenoid. The cable center wire is connected to 13a, the ground braid to 13b.

cade, these too become flux trappers. The highest fields are obtained when all three cascades are used. As noted later, some of our experiments were done with only two cascades to permit a larger initial experimental volume.

Owing to obvious shipping restrictions, all components made of or requiring explosives were made at Los Alamos. Besides the main cylindrical charges, small amounts of explosives were also required for the initiation blocks. There were enough new features in the explosive systems that we decided to make a general compatibility test. Figure 2 shows the test setup. Only three initiation blocks were used instead of ten that are required for the complete assembly. These were symmetrically placed over a Composition B hemicylinder. An aluminum liner served as a crude mockup of the first cascade. The test results: confirmed that the implosion was smooth, as determined from a framing camera picture sequence of the liner surface; confirmed that firing the initiation block detonators in parallel at 2500 volts was satisfactory; and supplied the crucial timing from load ring to inner charge diameter, through use of judiciously located shorting pins.

SYSTEM TESTS

Two complete system tests were made before embarking on the rather complicated superconductivity studies. The tests had a dual purpose: to check out the entire system and to obtain some code benchmarking data.

In both shots, all three cascades were used to get maximum fields. The first (solenoid) cascades were powered by two modules (3000 μ F each) of the Ancho Canyon Site capacitor bank. A bank charging voltage of about 18 kV was sufficient to generate the 2.0 MA normally used. This current generated an initial field of about 16T in the center of the system.

The Russians use a 50/50 mix of RDX/TNT explosive for the main charge. For the benchmarking tests we used two different explosives: Composition B (60/40 RDX/TNT) and PBX 9501. Composition B was used for the remaining three shots in the series.

Magnetic fields were determined in two ways: integration of voltages obtained from calibrated B-dot inductive probes, and the measurement of Faraday rotation of plane, polarized light through a standard material

The first method has been used at Los Alamos for decades. Probe calibrations are obtained from a special capacitor bank-coil system set up for this purpose. Both the probe of unknown area and a standard probe, whose area is accurately known, are placed inside the coil. Comparison of the signals obtained when the capacitor bank is fired gives the area of the probe under calibration in terms of the standard probe area.

On the other hand, the Russian team generally uses the Faraday rotation method.¹ This measurement is often supplemented with B-dot probe measurements, but the Faraday measurement is the primary one. Their standard arrangement employs He-Ne laser light (0.6328- μ m) and a standard, heavy flint glass as the optically active medium. We used both methods here. Figure 3 gives an enlarged view of the third cascade. The first shots were heavily diagnosed. Three different Faraday sensors were used. They were placed in 1-mm wall ceramic tubes (2-mm. ID). Two B-dot probes, encased in shrink tubing, were nested between the ceramic tubes. Finally, a single-mode optical fiber was nested between two of the ceramic tubes, and the Faraday rotation of light in the fiber measured the current flowing through the cascades².

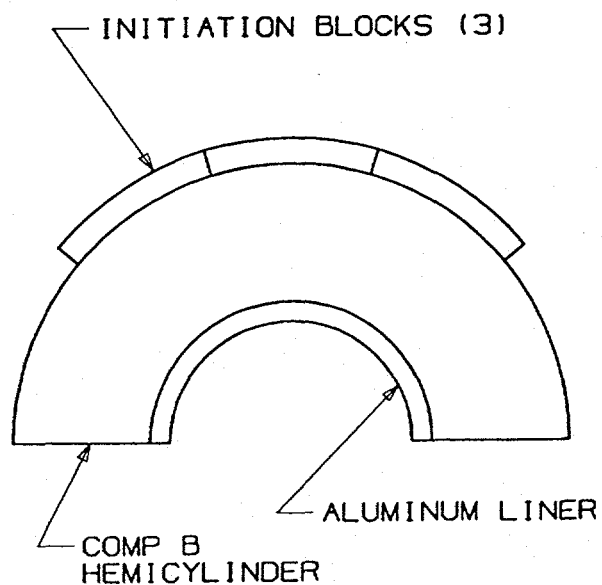


Figure 2. Cross sectional view showing the components used in the LANL-Arzamas-16 explosive compatibility test.

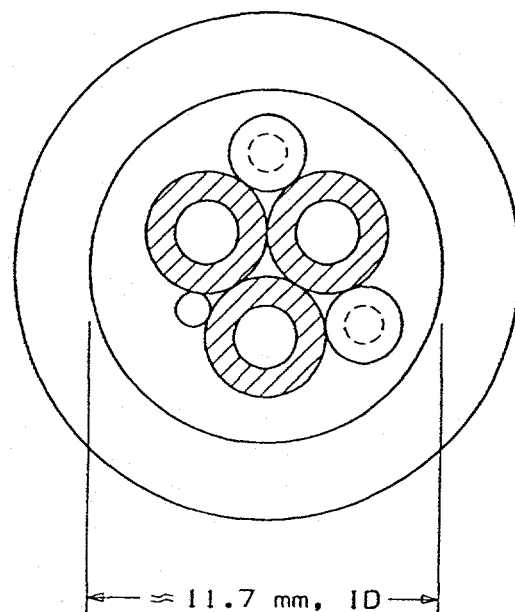


Figure 3. Sketch showing the location of various diagnostics inside the third cascade.

The actual Faraday rotation packages are rather complicated. Figure 4 gives an enlarged view. For field measurements, the sensor rods were made from a standard flint glass supplied by the Russian team. A detailed description of the sensor construction and the analyses of the Faraday signals are given in appendices of Ref. 2.

Figure 5 gives a plot of magnetic field vs. time for the two benchmarking shots. We were highly pleased with these first tests since they showed us that our fabrication, firing and diagnostic techniques were satisfactory.

The main explosive charges were made well in advance of the series. Four of them were of Composition B, a stock LANL explosive closest to that normally used by the Russians,

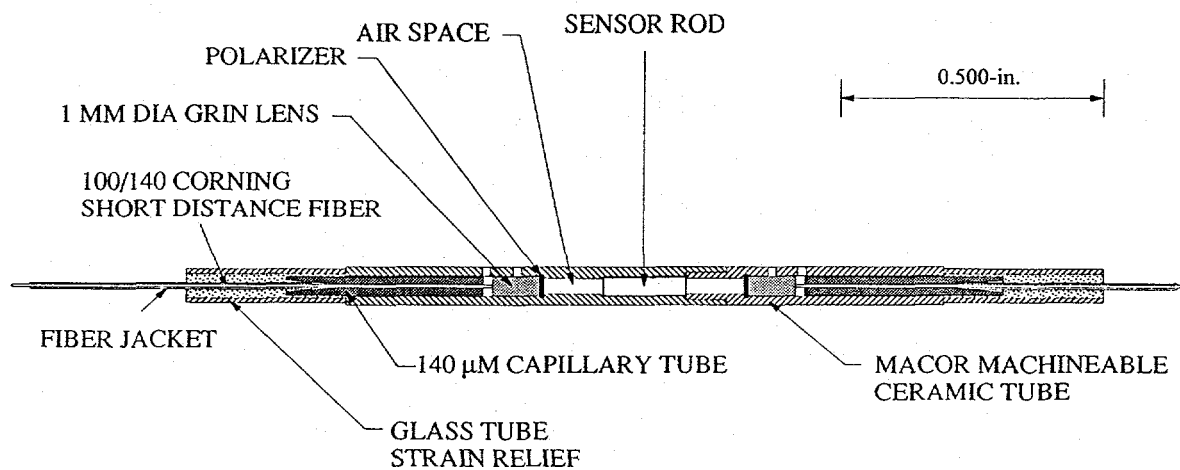


Figure 4 Enlarged view of Faraday assembly. Standard flint glass sensors were used for magnetic field measurements. Other sensors used included fused quartz and CdS.

although somewhat more energetic. In view of its excellent performance, the more energetic PBX 9501 explosive will probably be used in future shots.

YBCO CRITICAL FIELD

The low temperature critical field of YBCO perpendicular to the C-axis is known to be large. Indeed, one of our earlier estimates gave an upper limit of 900T for this field! This value was thought to be too large. Therefore, early in the planning stages of the test series, it was decided to try to measure this field using the MC-1 generators. The experimental setup used is shown in Fig. 6. The YBCO samples S of Fig. 6, were epitaxial thin films (100 μm) plated on sapphire substrates, with the C-axes perpendicular to the substrates, and thus also to the magnetic field, B. An interferometer centered at 94 GHz recorded amplitude and phase information for both transmission and reflection from the sample. These data were then used to determine the high frequency, complex conductivity of the samples vs magnetic field (after Ref. 4). The 94 GHz radiation was carried by standard WR-10 waveguide up to the high field region, where it was then replaced by dielectric waveguides. Metallic guides, if continued into the sample region, would be squashed by the large fields besides perturbing the fields near the sample. The small guide dimensions, and thus the high frequency, were dictated in part by limitations of the experimental volume available at high fields.

The foam cryostat C, housing the sample and wave guides, had an outer diameter of 28 mm, and fit snugly inside the second cascade. The third cascade was not used in these experi-

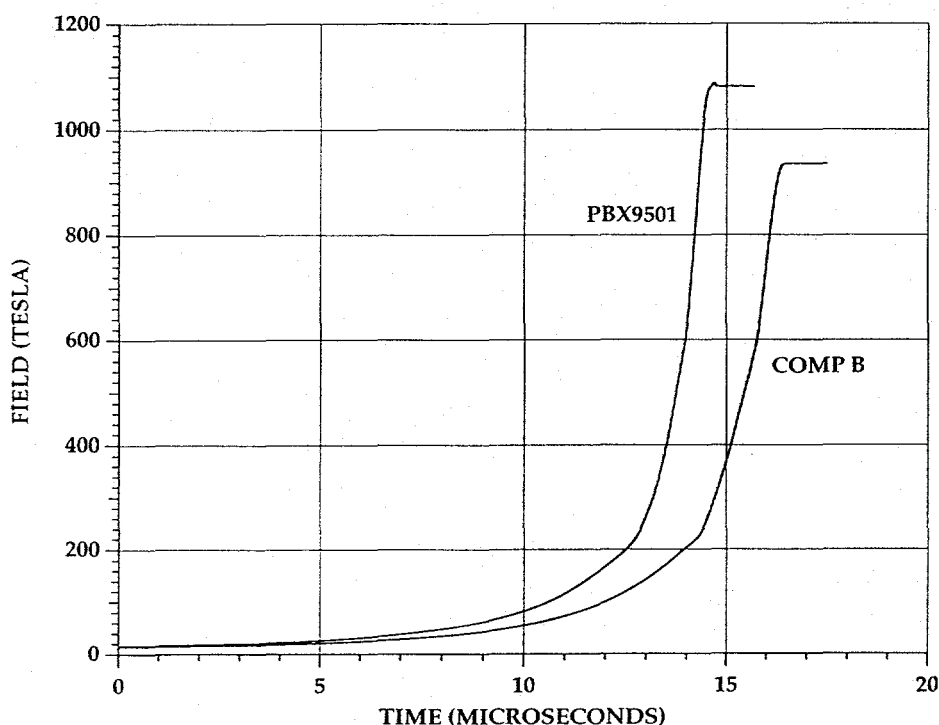


Figure 5. Comparison of field records obtained with Composition B and PBX 9501 charges. Time scales are adjusted so that zero time corresponds to the onset of flux compression.

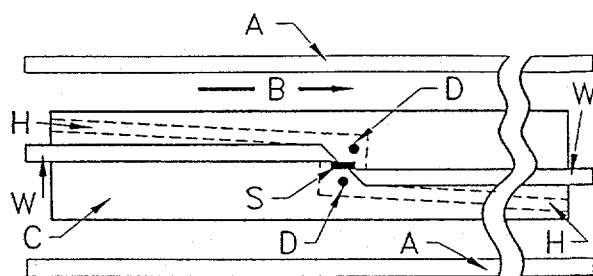


Figure 6. Diagnostics for YBCO studies. A is the imploding liner, B shows the magnetic field direction. C is the foam cryostat that fits snugly inside the second cascade. D's are temperature sensing diodes, H the helium cooling channel, S the sample, and W the dielectric waveguides.

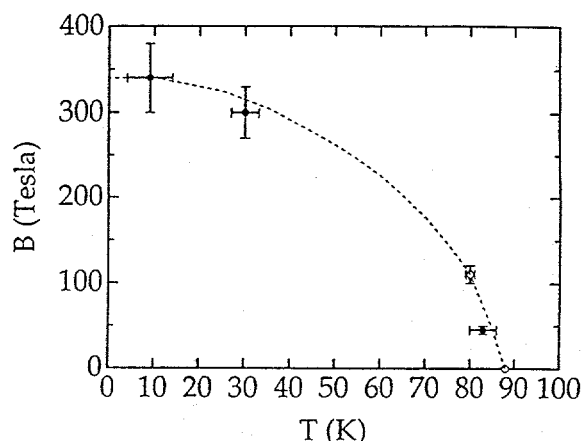


Figure 7. The critical field B vs T for YBCO. The 80 K point is from earlier work.

ents. Cooled helium gas or liquid helium was flowed through the ports labeled H. Temperatures were monitored by two Si diodes shown as D in Fig. 6. Both inductive and Faraday rotation probes were used for field measurements. They were placed in the cryostat as close to the sample as possible without interfering with the other diagnostics.

Analysis of the transmission and reflection data⁴ gave values of the complex conductivity. Vanishing of the imaginary part of the conductivity is assumed to mark the end of the superconducting state. Results from two shots are shown on Fig. 7. These data, together with earlier low field data, furnished the dashed line as a guide to the eye. We assign a value of 340 ± 40 T as the low temperature critical magnetic field.

ACKNOWLEDGEMENTS

Many contributed to this program without whom it could not have been done. Among them were people involved in firing point activities, explosive fabrication, diagnostic construction, machining, data acquisition and analysis, sample preparation, safety, security, logistics and language translation. Space prevents acknowledging them here, but the authors encourage the reader to consult Ref. 2 which more adequately recognizes these talented people.

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