SUPPORT TO SURVIVABILITY/VULNERABILITY PROGRAM

Steven W. Seiler

Logicon R&D Associates
2600 Yale Boulevard, SE
Albuquerque, NM 87106

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PHILLIPS LABORATORY
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This technical report has been reviewed and is approved for publication.

JAMES H. DEGNAN, GS-14
Project Officer

FOR THE COMMANDER

ALLEN L. CHESLEY, Major, USAF
Chief, High Energy Plasma Division

BRENDAN B. GODFREY
Acting Director, Advanced Weapons and Survivability Directorate

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Steven W. Seiler

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Logicon R&D Associates
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Albuquerque, NM 87106

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This report includes analytic discussion of use of company toroid as magnetized target for compression by solid liner implosion and reports on design and diagnostics for the Phillips Laboratory MARAUDER compact toroid program. Diagnostic work included fielding 20 to 30 magnetic probes with analog fiber optic links and fast photography. The latter required modifications to the MARAUDER triggering system. Design features of factor three conical compression hardware are discussed.

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INTRODUCTION

An analysis and design and development study was conducted for the MARAUDER Compact Toroid program on the Shiva Star capacitor bank in Building 322 of Kirtland Air Force Base, New Mexico. One of the goals of the MARAUDER program is to provide an X-ray source for survivability/vulnerability testing of Air Force systems in nuclear and nonnuclear threat environments. Such tests must employ either underground nuclear tests or laboratory simulations that can produce sufficient energy density and spectrum at the test component to accurately match a given threat. The MARAUDER program seeks to develop a nonnuclear test system that is based on a high-energy-density plasmadynamic acceleration of a plasma compact toroid to velocities in excess of 1,000 km/s. A plasma projectile of this level of velocity can be used to directly impact on a test object to simulate the energy density of a variety of directed energy weapons. The plasma can also be stagnated and thermalized to temperatures in excess of 10 keV to provide a high-power source of X-rays to simulate a nuclear threat to space-based assets.

The study was divided into two major tasks: Task 1 - Analysis and Task 2 - Design and Operation. Under the analysis task, a new conceptual application of the MARAUDER approach that utilizes the compact toroid as a magnetized target for a subsequent implosion driven by a high-speed solid liner was investigated. Under the design and operation task, support was provided for the design and development of new diagnostic systems and of upgrades to the MARAUDER acceleration and compression hardware.

TASK 1: ANALYSIS SUPPORT

The MARAUDER program at Phillips Laboratory (PL) is similar to the approach proposed by J. H. Hammer, et al., for the RACE program at Lawrence Livermore National Laboratory (LLNL) (Refs. 1 and 2) for the acceleration of compact toroids. A compact toroid represents a self-contained configuration of plasma and magnetic fields. The self-consistent toroidal and poloidal fields within the compact toroid are nearly parallel to the electrical currents that are sustained by the high-temperature plasma. This represents a nearly force-free situation that can remain stable as long as the currents can be maintained against resistive dissipation. For toroids of the size and temperature of the MARAUDER program, the lifetimes are predicted to be of the order of hundreds of microseconds. This is long enough to allow the toroid mass to be electromagnetically accelerated to velocities of 1,000-10,000 km/s.

In the MARAUDER program, a compact toroid is first formed with a diameter of approximately 1 m. It is then compressed by a factor of three in radius to increase the internal magnetic field energy and energy density. The compressed compact toroid is then electromagnetically accelerated to high velocity in a coaxial plasma gun. The high-energy density is achieved through the conversion of stored electromagnetic energy from the Shiva Star capacitor bank into plasma kinetic energy. If a high-Z plasma with 4 MJ of kinetic energy were stagnated and thermalized in a time scale on the order of 10 ns, hundreds of terawatts of X-ray radiation could be produced.

Another potential application of the MARAUDER technology that was reviewed would be to use a deuterium/tritium (DT) compact toroid as a magnetized target load for a cylindrical or quasi-spherical implosion driven by a solid heavy liner. The work of Lindemuth and Kirkpatrick (Ref. 3) has shown a parameter space for magnetized fuel targets in inertial confinement fusion that may be accessible through utilization of the Shiva Star capacitor bank.

The application of a DT compact toroid may provide a unique and viable method to produce an initial magnetized fuel region that could be injected in the foci of an imploding heavy liner that will provide the external energy drive to shock heat the DT fuel to fusion conditions. The enclosed magnetic field configuration of the compact toroid will significantly reduce or eliminate thermal conduction losses on compression, and the implosion will be a more nearly adiabatic process than implosions in conventional parameter space. A second positive effect can be the Ohmic heating that occurs as magnetic flux is dissipated during the implosion. A detrimental effect due to the presence of the magnetic field is that the additional work is required to compress the toroidal field; however, the two-stage compression concept will account for this compressive loss mechanism.

In order to provide an initial assessment of the concept, it is useful to perform calculations of the fusion yield with some simplifying assumptions. First, assume that a DT compact toroid with a mass on the order of 19 mg and a volume on the order of 30 cm^3 (3-cm diameter x 3-cm high) can be injected into the foci of an imploding heavy liner and, second, assume that the initial ion temperature is on the order of 1 keV. The thermal energy of the injected toroid is, therefore, on the order of 740 kJ. If the imploding liner with an implosion energy of 5 MJ can provide compression of a factor of 30, then the DT will be adiabatically compressed to about 10 keV. The reaction rate $<\sigma v>$ (in cm^3/s), averaged over a Maxwellian distribution for low energies ($T < 25$ keV) may be represented by

$$<\sigma v>_{DT} = 3.68 \times 10^{-12} T^{-2/3} \exp\left(- \frac{19.94}{T^{1/3}} \right) \quad (1)$$

The power density released in the form of charged particles (alphas) is given by

$$P_{DT} = 5.6 \times 10^{-13} n_D n_T <\sigma v>_{DT} \text{ W cm}^3 \quad (2)$$

Substituting the assumed values at peak compression into Equations 1 and 2, yields a fusion output power density of 3.3×10^{14} W. Thus, assuming a 30-ns confinement, the output fusion energy into alphas that will heat the fuel is 10 MJ. This fusion yield will produce a fast neutron fluence of 1.8×10^{19} neutrons in 30 ns. This would represent $> 10^{14}$ n/cm^2 at

1 m from the source and provide a significant pulsed neutron simulation in addition to the X-ray output.

If the imploding liner is a 10-cm-dia molybdenum foil, 3 cm high, 30 μm thick, then the liner will weigh 2 g and will have an implosion velocity ~ 7 cm/μs for a kinetic energy of 5 MJ. This mass of liner represents about 6.25 x 10^{21} atoms. If the fusion yield is deposited in the DT and then mixes with the liner, then the liner (Mo) will have on the order of 7 keV/particle deposited in the 30 ns. One could expect this system to be a very interesting warm X-ray emitter.

These simple calculations indicate that an innovative load design that incorporates injection of a compressed DT compact toroid into the foci of an imploding liner may be attractive as a possible candidate for a magnetized target fusion concept with parameters to reach ignition within reach of existing machines. The present analysis neglects many important loss mechanisms and thus must be explored in more detail in the future. The two-stage compression concept may require significantly more second-stage implosion energy than assumed here and, therefore, the concept should be reevaluated with the use of an explosive flux compression generator. Also, the use of a fissile imploding liner to provide additional prompt heating of the liner to improve efficiency as a radiator should be examined in more detail.

TASK 2: DESIGN AND OPERATION

TASK 2.1: MARAUDER DESIGN ACTIVITIES

The design support activities included the analysis and redesign of the outer conical acceleration electrode to minimize the separation of the compact toroid from the outer electrode during the initial stages of compression. Figure 1 shows the configuration of the MARAUDER experiment. As the compact toroid enters the expansion/trapping region, its outer boundary expands and its mass density decreases. If the expansion is too great, the mass density and magnetic field strength become too low to keep the toroid in contact with the outer electrode when the accelerator bank current and driving magnetic field begin to increase. This allows the toroid boundary to lift off the outer electrode and let the driving flux expand rapidly into the gap. This separation may have been the cause of voltage surges on the accelerator bank vacuum feed due to the rapid increase in system inductance from plasma motion. It is also possible that the rapid increase in inductance is due to the accelerator bank field pushing the debris plasma remaining in the coaxial plasma gun back toward the formation gun insulator. Further study is required to determine the exact cause of the voltage surges and will take place during the next series of experiments.

These voltage surges have caused breakdowns in the accelerator bank feed slot and prevent proper plasma compressions. The original vacuum feed design is shown in Figure 2 along with the modified design that was analyzed. Some design modifications that were performed included the addition of a full, continuous brazing of the lower copper feed baffle to prevent arcing and to prevent vacuum ultraviolet (UV) from the plasma from illuminating the upper insulator region. In addition it was recommended that the lower portion of the outer vacuum chamber wall that forms part of the feed baffle be cut back and a field grading ring be added to minimize the electric field gradient at the corner and reduce the reflected UV radiation that can reach the upper vacuum insulator region. This modification has not yet been implemented.

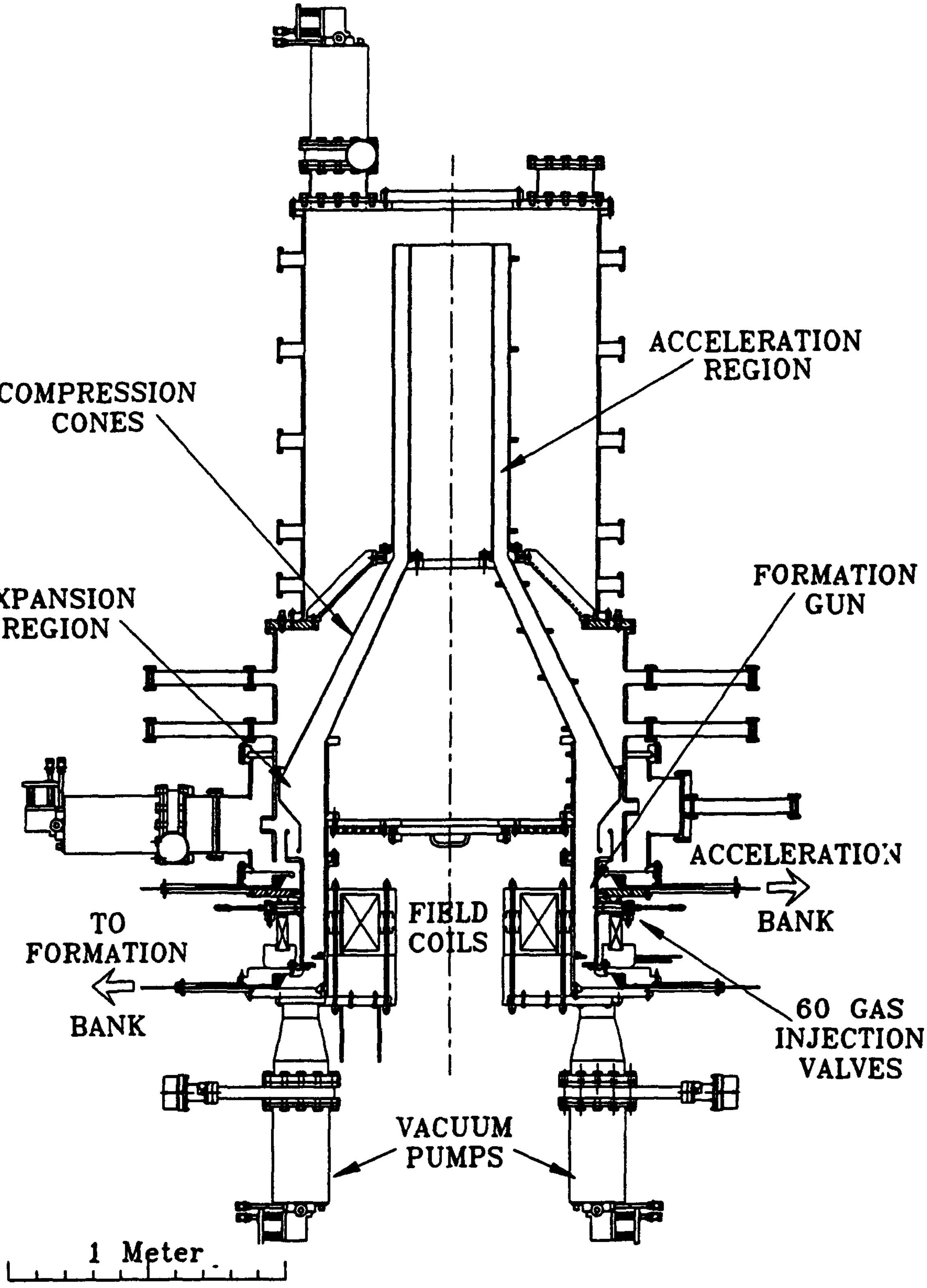

Figure 1. The MARAUDER assembly drawing.

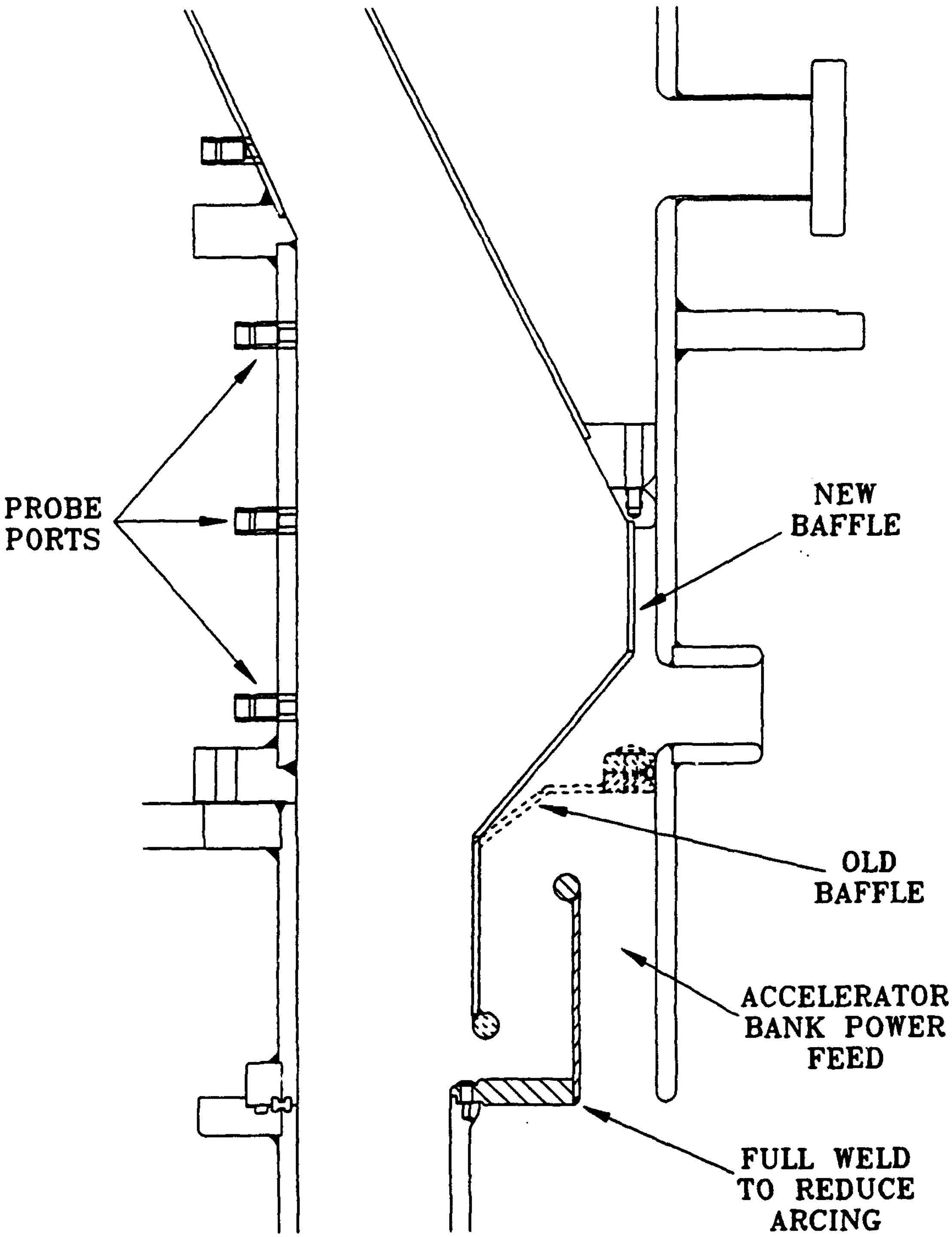

Figure 2. Detail of MARAUDER accelerator feed showing both old and new baffles designs.

On-site investigation of the damage patterns also revealed that the current joint at the junction of the inner conductor and inner conductor extension were not properly matched and were causing arcing that was injecting impurity plasma into the discharge. The inner conductor extension was remachined to correct the problem.

The theoretical analyses performed have shown that better compact toroid compression could be achieved with compression electrodes that maintain a self-similar conical geometry. The electrodes used during this study did not maintain a constant radius ratio between the inner and outer cones. A constant radius ratio requires that the apex of the inner and outer conductor cones meet at the same point on the centerline. Using parameters that were provided, the design concepts shown as the crosshatched areas in Figure 3 were drawn.

The material choice for the proposed self-similar compression electrodes was investigated. The existing hardware is made primarily of stainless steel which is a good material for high vacuum systems, but has surface oxide layers and large resistive losses that produce plasma impurities and drag on the accelerating toroid. Refractory metals for electrodes were investigated by the RACE group at LLNL and not found to be beneficial (private communication from J. Hammer of LLNL). Copper has the advantage of reduced resistive losses but is structurally weak by itself, is very difficult to machine, and still forms oxide layers. Copper plating of stainless electrodes was extensively investigated by Physical Sciences, Incorporated (PSI). Among the companies contacted were: Kaehr Plating, Albuquerque, NM; Custom Microwave, Denver, CO; Gamma-F Corporation, Torrance, CA; and A. J. Tuck Incorporated, Brookfield, CT. The strength, surface finish, and adhesion of plated copper on stainless electrodes were determined to be adequate, but no company was located that could produce the required thickness on objects as large as the compression electrodes. During the discussions with a number of electroplaters, it was discovered that organic materials which are used in the plating solutions (formaldehyde in one case) are often entrained into the grain boundaries of the copper. These materials could contribute to the plasma impurities generated by the discharge at the electrode surface and would have to be removed by extensive bake-out procedures that the present MARAUDER system is not

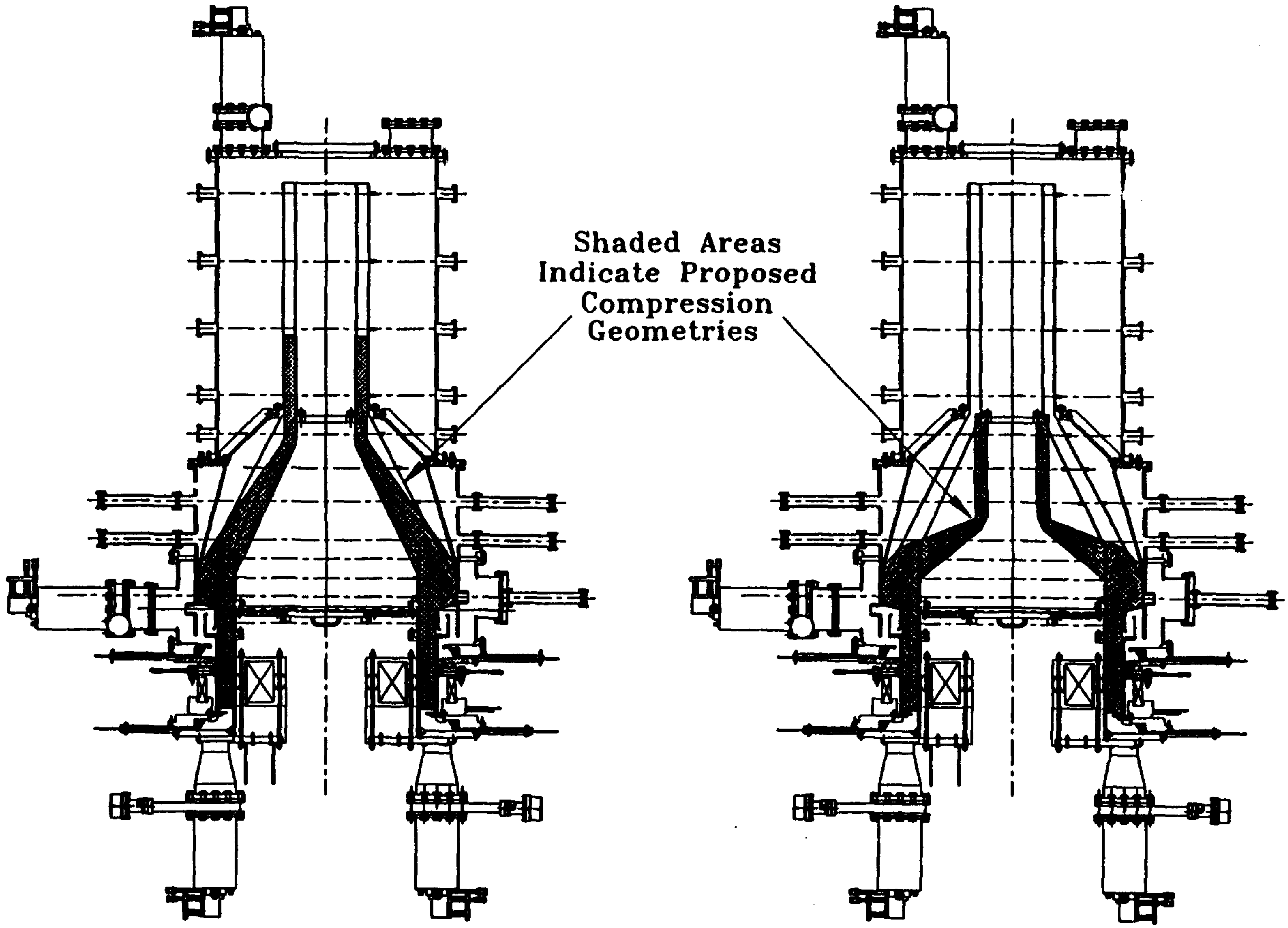

Figure 3. Two proposed improvements to the compression cone design.

designed to accommodate. It was recommended that a set of conical electrodes be made using solid copper sheet formed onto backing rings and flanges of stainless steel or brass. The current joints would be made by rolling the copper around the stainless end flanges. The amount of actual machining of copper would be minimized to reduce the cost and all the required O-ring seals would be machined into the stainless flanges. If early tests by the LLNL group indicate that it is beneficial, thin gold plating of the electrode surface could be used to minimize the surface contamination.

TASK 2.2: MARAUDER DIAGNOSTIC ACTIVITIES

The diagnostic support activities included the modification and operation of a high-speed turbine mirror framing camera (Beckman-Whitley model 189) and the conceptual design of a 24-channel fiber optic analog data link system for use with the magnetic field probes and the digital data acquisition system.

The fast framing camera diagnostic on the MARAUDER experiment has been one of the primary means of measuring discharge symmetry and breakdown problems. It was normally performed by a high-speed camera that had to be transferred to another experiment within the PL. The replacement was a government surplus system that required modifications to be compatible with the triggering and timing system of the MARAUDER experiment. The PSI modified the control electronics to allow the camera to be operated from the Shiva Star control room and have all of its timing signals transmitted to the Shiva Star screen room over fiber optics. The camera was set up on the MARAUDER experiment and the triggering and timing system connected to the MARAUDER system. Its timing and operation were tested using a high-power flashlamp to simulate the MARAUDER discharge. The PL was briefed on the operation of the camera system and the procedures for loading and developing the film.

In support of the magnetic field probe diagnostic system on MARAUDER, PSI in conjunction with PL performed the preliminary design for a system that would allow the radial position of the probes in the inner conical electrode to be varied without having to vent the vacuum system. The system involves the use of Ultratorr vacuum feedthroughs coupled to flexible cable drives. The cables in turn are coupled to the probes by nested tubing that both supports the probe and prevents it from rotating during radial movements. The types of cables and the requirements for vacuum compatible materials and lubricants were discussed with PL personnel and conceptual design sketches provided to allow fabrication by other PL contractor personnel.

The magnetic field probe system for the MARAUDER experiment requires the addition of more data channels to allow better mapping of the discharge with fewer shots. As part of this upgrade, PL has purchased 24 channels of high-speed digitizers to be used in addition to the existing oscilloscopes. To transmit the additional probe data to the screen room, 24 more channels of analog data links are also required. In consultation with PL personnel, PSI performed the conceptual design of a system that would be compatible with the digital data acquisition system under development for the Shiva Star screen room.

The design recommendations included having the transmitters battery operated and with fiber optic controls for both power and self-calibration operation. The 24 channels could be configured in a variety of ways, but the final recommendation was to have 9 channels of individual transmitters and 15 channels with 3 transmitters in a single enclosure. The receivers in the screen room should be configured as 2 rack mount crates, each containing 12 channels of receivers and all the fiber optical control signal systems needed to operate and calibrate the transmitters. The calibration signals that are internally generated by the transmitters must be compatible with the digital data acquisition system. This requires that they be synchronized with the digitizer triggers and that the waveform be used to both calibrate and linearize the complete data link system for either positive- or negative-going signals. The recommended set of waveforms included a precision linear ramp with a selectable ± 1-V amplitude and 5-μs duration with a fast fall time, and a fast rising square pulse of ± 0.5-V amplitude. The pulse shape and direction should be selectable from the screen room and the pulse timing synchronized with a trigger pulse output to the digitizers. The linear ramp can be used to perform a polynomial fit to allow the signals to be corrected for both amplitude and nonlinearity. A simulation of a test waveform indicated that a fourth-order curve fitting would be adequate to correct the actual B-probe data. The appropriate equations for a fourth-order fit were derived to allow the generation of a stand-alone fitting routine to be written that would take up less memory and run faster than commercial data analysis software. The digital analysis should record the derived fitting parameters along with the raw data prior to archiving.

In addition to providing single shot calibration signals that are best for digital data acquisition systems, the data links should be able to produce repetitive signals that are best for visual calibrations using standard oscilloscopes. To prevent problems with the AC coupling that are inherent to the data links, the waveforms should have alternating positive- and negative-going pulses to prevent the generation of offsets.

In support of the PL diagnostic activities for MARAUDER, two battery-operated photomultiplier tube power supplies were designed and assembled. The design used commercially available DC-DC converters and rechargeable batteries in a shielded box. The output voltage was adjustable from 600 to 1,100 V to allow for gain control on the photomultiplier. A current- and voltage-regulated charging supply was also fabricated for the power supplies.

CONCLUSION

The ongoing MARAUDER program has the potential to provide an enabling technology for many high-energy density applications. In addition to the primary goals of plasma projectiles and high-power flash X-rays for survivability/vulnerability verification, the compact toroids produced may be useful for high-speed vacuum opening switches, high-power microwave source development, and fusion/fission sources for weapons effects testing and weapons physics experiments. There appear to be no fundamental physical limitations that would prevent the success of MARAUDER in achieving its velocity and energy-density goals. However, in order for the potential of the MARAUDER program to be realized, great care will be required in the future to minimize the effects of plasma impurities produced by the electrode surfaces. This will involve improved vacuum handling techniques, wall surface treatments to reduce contamination, and better current joints to reduce contact arcing. Improved diagnostics for the determination of the sources and diffusion of wall plasmas may be needed to better quantify the problems and to guide the development of future hardware designs.

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