SAND--97-0333C

WATER-LINE DESIGN AND PERFORMANCE OF Z

CONF-9706113--

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Abstract

A new set of bi-plate transmission lines have been designed and installed in the water-section of PBFA-II for the Z-pinch experiments. Thirty-six aluminum flat-plate transmission lines submerged in a water dielectric deliver a timed electrical pulse from coaxial tube sections to a ring stack section. Each of the lines are electrically isolated from each other by transit-time effects.

The water-lines are configured radially at four vertical levels. Each level has nine sets of bi-plates, with a transition section that is unique to that level. Mechanically, the bi-plate sections are designed to carry both static and dynamic loads. Electrically, the lines are designed to transport electrical pulses that average 200 nanoseconds with peak voltage of 2.5 to 3.0 MV. The peak fields exceed 200kV/cm. All line sections are a series of chromate coated aluminum plates, broken down into short, light weight sections.

The design of the plates was meticulously developed using the Electro[1] code for voltage break down, and NISA[2] for mechanical analysis. Electrical losses associated with impedance mismatching and voltage break-down were carefully reviewed. Changes in the bi-plate gap, surface shapes and electrical path discontinuities (mechanical joints) were precisely calculated to achieve maximum electrical performance and reliability. Several iterations of surface shapes and line gaps were reviewed to achieve the most desirable characteristics possible. Additional criteria required that minimal time and effort be required to remove and install the water-lines. Special hardware was developed to help meet this requirement.

Introduction

Z is a single pulse, Z-pinch accelerator[3], (figure 1) designed for inertial confinement fusion and weapon physics experiments. It measures 33 m in diameter and 6 m high (figure 1). The machine is divided into three sections: the oil section containing 36 Marx generators, a water section containing 36 coaxial lines, an insulator stack, and a vacuum section containing the MITLs [4,5] and Z-pinch load. The water section defines the electrical path and characteristics of the pulse shape. Thirty-six coaxial capacitors submerged in di-ionized water receive the electrical charge from the Marx generators located in the oil section. The electrical energy is then discharged through laser-triggered gas switches into coaxial arrays of self-break pulse-sharpening switches. The energy then flows through transitions sections that have a geometry change from coaxial to bi-plate transmission lines. The bi-plates connect to rings on the insulator stack. Four MITLs carry the current radially inward through a double-post hole convolute and into the Z-pinch load located at the center of the machine.

DISCLAIMER

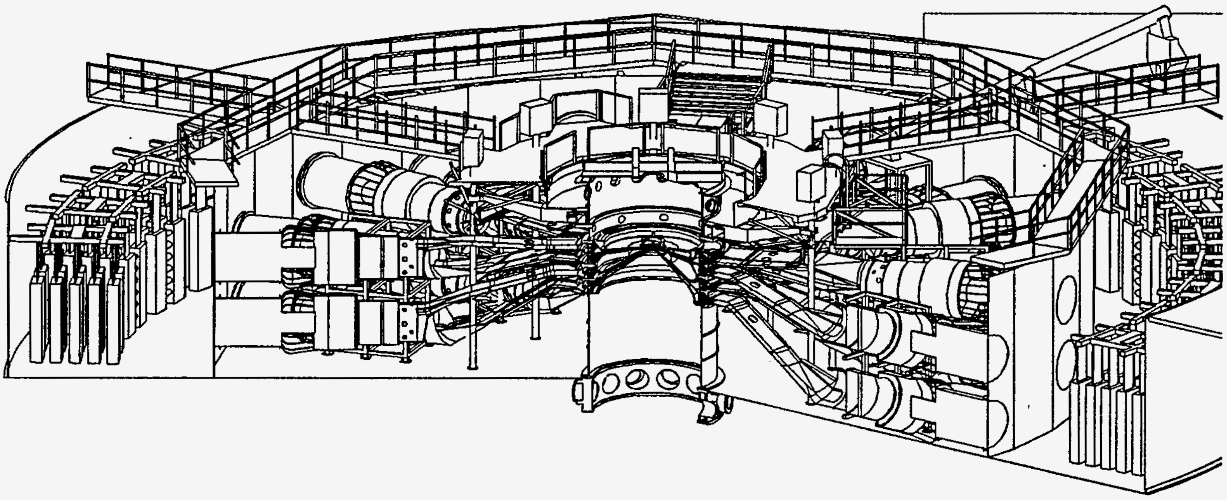

Figure 1. Z accelerator with Marx oil tank, water-lines and center stack.

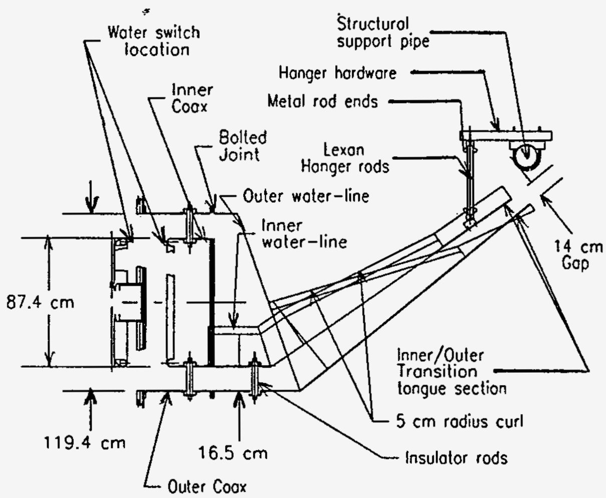

Figure 2. Typical water-line details.

Water-line Function

The inner and outer coax lines (figure 2) are 87.4 cm and 119.4 m in diameter, respectively and are stacked in four levels distributed in pairs at eighteen azimuthal locations. The inner and outer coaxial lines begin as a pair of horizontal, concentric (coaxial) tubes with 16.5 cm gap, then transition into flat parallel (bi-plates) lines with a 14 cm gap. The first three levels must slope upward to meet the elevated stack ring, while the fourth (top level) is nearly horizontal. The sloping of the lines has an inherent design advantage because it also reduces bubble entrapment, a significant consideration in high voltage design. Finally, the water-lines return to a horizontal orientation at the wing section and converge radially to the diode ring stack. The geometry of the water-lines has four variations, each unique to its level, with the slope of each line varying from 39 to -1 degrees .

System Architecture

The water-lines are 4.8 mm thick, alodine-coated 5052-H32 aluminum alloy and are divided into three radial sections. The first are the inner and outer transition weldments (figure 2), the second are the bi-plates (figure 3), and the third are the wing sections. The outer water-line section is a single weldment bolted to the outside portion of the coaxial cylinder. It is the largest and most complicated of all the pieces beginning with a rolled flange and ending with a formed transition tongue. Compound shapes were required to transition smoothly from coaxial tubes to flat plates, while maintaining an edge curl with a tapering gap (figure 3). The ideal design of this piece would require die forming due to its complex geometry. Cost and scheduling requirements however, led to an acceptable approximation of the design using a more conventional manufacturing technique. The inflection of the curl is unique to the outer water-lines.

The inner water-line weldment (figure 2) is nested within the outer water-line and bolts to the smaller coaxial tube. It is composed of four individually formed and welded sections with curled edges. The inner line has a different overall length from the outer line to reduce electrical arcing at the flat plate joints. The hanger hardware attaches to this weldment section and is shown in figures 2, 5 and 8.

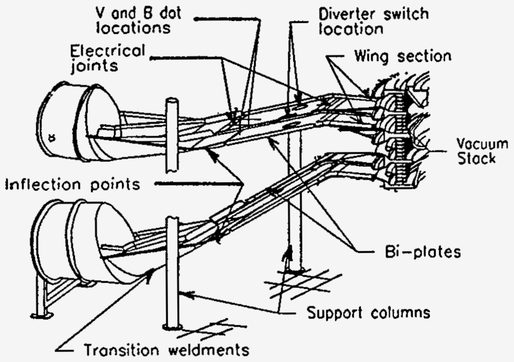

Figure 3. Water -line sections.

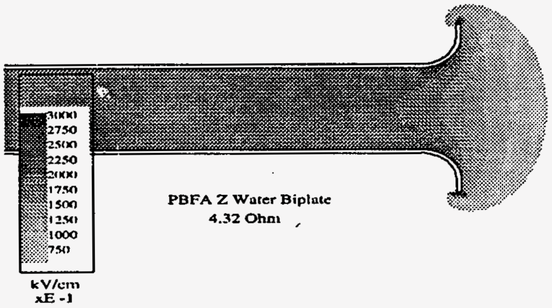

Figure 4. Electrical field plots of typical curled edge with a peak field of 300 kV/cm on the outer edge of the curl.

The bi-plates (figure 3) are the simplest water-line components and the last of the assemblies be to installed. The bi-plates vary in length for each level and include riveted stiffeners and curled free edges. Each bi-plate also contains a pair of resistive diverter switches (figure 3) that dissipates electrical energy reflected from the insulator stack which reduces arcing damage to the water-lines. The ground side of the bi-plates also contains voltage and current monitors[6].

The last section contains the wings which are bolted to the flared stack electrode rings prior to installation of the bi-plates. The aluminum alloy wings adopt to the bi-plate angle of each level. They are nickel plated and continue the edge curls from the bi-plates to the flared rings on the stack.

To maintain the required electrical characteristics and constant impedance of 4.32 ohms, good electrical contact at the mechanical joints was required. Also, constant plate gaps of 14 cm had to be maintained to within 5%. The water-line sections were designed with overlapping joints and were clamped in place. High current contact is achieved by nickel plating the contact surfaces of the aluminum plates. The mating joints included a 6mm thick stainless steel plate riveted in a double rows of alternating spaces designed to carry a moment load. The overlapping arrangement of the riveted plates allow for each bi-plate to be installed by resting on the wings and transitions parts. The bi-plate design therefore, alternates in pairs, half with the riveted stainless steel tongues and the other without the riveted stainless steel tongues.

Edge curls of all free edges were designed to reduce electrical field enhancements. The free edges have a formed 5 cm radius curl. A field stress analysis on the curled edges of the plate was performed to insure low electrical fields[6] (figure 4) to minimize electrical arcing between the plates. This curl also adds considerable stiffness to the design.

The original design criteria stressed a need to minimize down time for alternating Z with the previous PBFA-II configuration. Special joint hardware (not shown.) was designed to reduce installation time. Toggle latches were used to provide electrical contact and single action sliding latches were designed to structurally support the load at the joints. All hardware mechanisms were designed to face away from the plate gap region.

Mechanical Loads

The water-line assembly was designed to take both static and impulse loads. The analysis allows for the dead weight of the lines as well as for a live load of 180 kg. The electrical pulse produces significant impulse forces in several modes. The first mode is from the self-break water switches (figure 2) located in the tube section of each water-line in which electrical energy must cross a water gap between two electrodes. When the electrical arc occurs, water is instantaneously vaporized, radiating a 6 KJ shock wave (from each gap) in all directions. Secondly, j x B forces from the current pulse will tend to separate the bi-plate pairs. Lastly electrical tracking and plate-to-plate arcs produce an additional shock wave similar to the one previously described.

In addition to absorbing mechanical loads, the components must to compensate for line length variations and allow critical plate-gap settings. The lines are partly supported by a hanger support system (figure 2) that attaches to existing columns in the water section and are connected by pairs of lexan rods. The electrical pulse on the water lines charges one end of the rods while the opposite end remains at ground. Transit time isolation helps prevent electrical break-down during the forward going pulse. However, this is not always the case when the reflected pulse arrives. When electrical tracking occurs across a lexan rod, the result is invariably destructive (figure 5).

Hanger Support System

A structural support system was required for the water-lines which would be adequate to carry the loads, provide a means for adjusting the plate gap, and interface with existing support structure while insulating the charged water-lines from ground. The types of impulse loads suggested that the design of the hangers should act like a suspension system. The electrical field enhancements of the components and physical shapes were carefully studied to reduce the possibility of voltage break down due to excessive electrical stress. The history of mechanical and electrical arcing failures on PBFA-II required a system that could easily be repaired, even under water. Our first design included a long, 2.5 cm diameter lexan rod clamped at both ends into a nickel-plated brass cap, 5 cm in diameter and 12 cm long (figure 5).

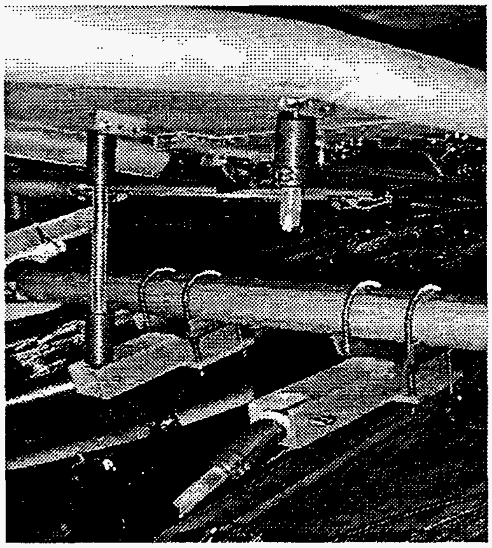

Figure 5. Water-line with broken rod.

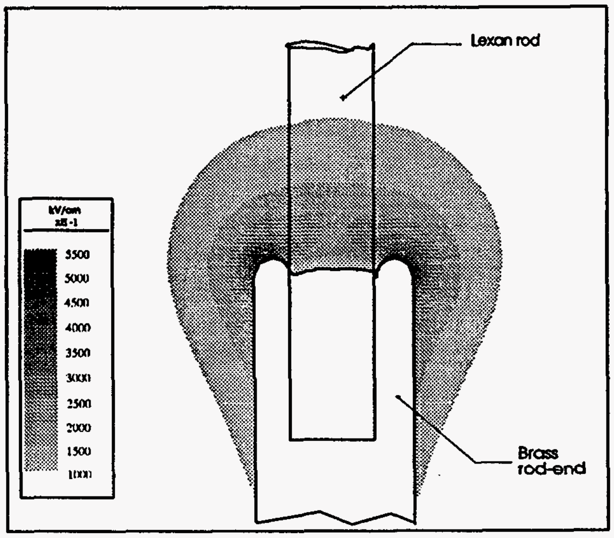

Figure 6. First generation rod-end, peak field 561 kV/cm.

The lengths of the lexan rods varied from 38 to 53 cm. Special features were incorporated into the design to eliminate the trapping of air bubbles. Threads were not used in order to eliminate any stress enhancement points. The rod was held in place by two recessed clamp screws so that the length of the assembly could to be adjusted with no threads on the rod. The design allowed for fine adjustment of the line gap by threading stainless steel ball-end joints into the brass end caps with left and right hand threads. This subassembly acts as a turn buckle, allowing for easy and precise final adjustment of the bi-plate gap. The ball end joints were chosen because they eliminated any bending stress in the lexan rod. The rods were preloaded, either in tension or compression depending on the need to open or close the gap between the plates. Quick release pins were used to connect to the hanger assembly for easy removal of the rods while under water.

Checking Fixture Design

To ensure the accuracy of the length of the water-lines, four welded metal fixtures were designed and built, one for each level. The water-lines were bolted in pairs just as they would in the machine and the lengths of the line pairs were checked for accuracy. A deviation of 6.3 mm of line length was acceptable.

Post-Engineering Problems

Several design and engineering problems were encountered while building the water-lines. The first centered around the manufacturing of the transition weldments . The weldments (figure 3) arrived with the plate geometry severely deviating from the drawing specification. The misshapen transition sections had become warped (figure 7) and would unacceptably alter the performance of the machine. It was unclear whether the parts were incorrectly made or that the material had distorted out of specification during shipping. To fix the problem special tooling was built and much stronger stiffeners were installed. To correct for the misshapen curves, special dies were used to adjust deviations into an acceptable shape. These corrections were performed in the field and proved to be acceptable.

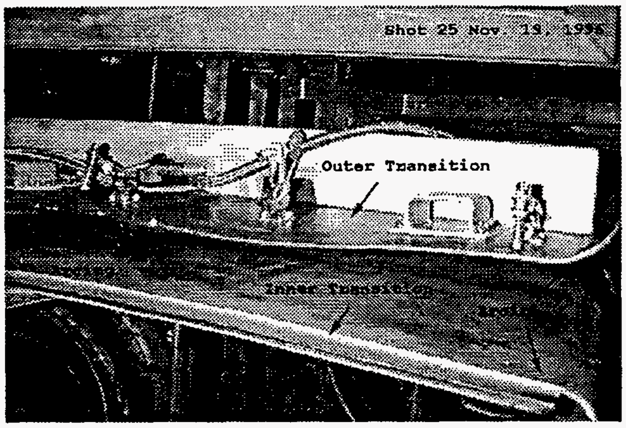

Figure 7. Warping of water-lines.

Following several shots on the machine, multiple lexan rod failures occurred (figure 5). The failures were caused by a combination of mechanical and electrical forces. Inspection of the rods indicated multiple arcs on each rod and eventual failure. It was felt that rod breakage was occurring during the reflected pulse. Nearly all the electrical and mechanical design concerns focused on the forward going pulse. The reflected pulse, as it turns out was more of a problem because it was much longer in time than the forward going pulse, and thus would add to the back-end of the forward pulse voltage and create numerous arcing failures. Closer electrical analysis determined that the peak the electrical stress on the brass rod end was 561 kV/cm (figure 6), almost twice the desired limit.

The problem with the high electric fields on the rod end assemblies was reanalyzed and several design changes were made. The lexan rod diameter was doubled to 5 cm and the overall length was increased to improve strength with greater voltage standoff capability. The brass end cap design was also changed to a bell shaped (figure 8, 9) geometry, with a major diameter of 89 mm and a radius edge. The lexan rod ends were threaded to mate with the metal end caps. The threads on the lexan rod were designed to be below the high electrical stress regions of the rod end piece. These improvements reduced the peak field from 561 to 350 kV/cm (figure 6, 9), dramatically reducing the rod breakage problem.

Another failure mode for the large lexan rods was mechanical compression. Rods broke in the center of the length. A force of 110.3 MPa is required to break the lexan rods. It has been suggested that the floor of the tank moves late in time due to the water section shock, which is then coupled to the rod hanger support system. Future modifications of this system to allow for this motion are planned.

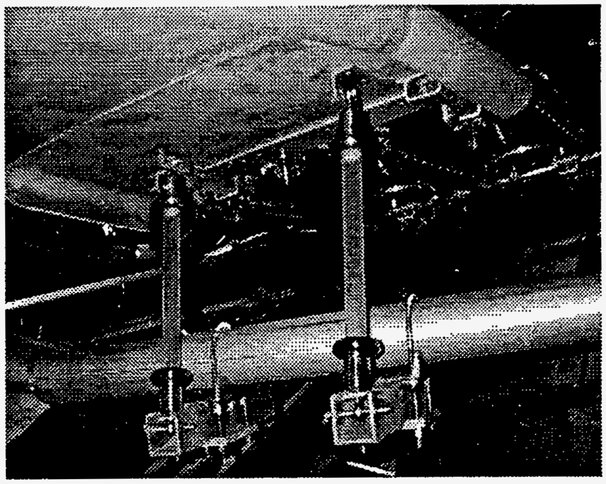

Figure 8 Water-line with broken rod.

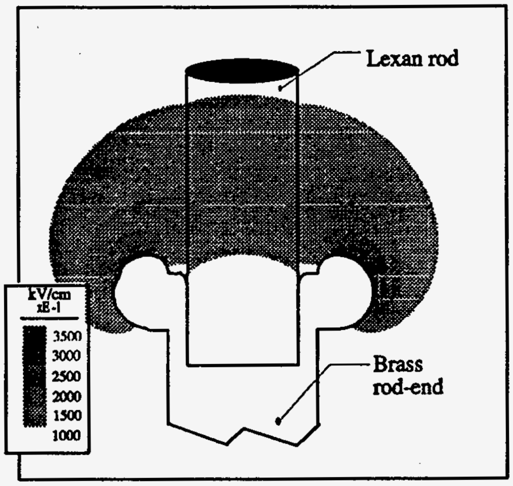

Figure 9. Field plots, new rod ends, peak field 350 kV/cm.

Peeling of the nickel plating has been observed and has resulted in one stack insulator failure. A piece of this plating migrated through the water and on to the stack section, causing an arc to occur. The arc damage was fatal to the insulator ring. The reason for the flaking is still unknown. One solution would be to eliminate plated components where possible by switching from aluminum alloys to stainless steel alloys, but the cost and weight increase of the components would balance against reduced risk.

Additional future modifications include better joint design to further reduce the electrical arcing problems at the transition sections. The sliding and clamping hardware is being replaced with robust bolted joints, since a return to the PBFA-II configuration has been programmatically eliminated.

Conclusions

A new and successful Z water transmission line system has resulted from an extensive design, engineering, and analysis effort. As with previous water section designs, a significant follow-up effort has been necessary to insure long-term reliability and efficiency in operation. Even as those improvements are implemented the search for lower impedance systems in the future will undoubtedly keep us close to the electrical and mechanical limits of reliability. Although system optimization will generally result from the balance of impedance with reliability, a special effort should be made to mitigate water-switch shock and late-time high-voltage breakdown in high-power accelerators.

*This work is supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

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M98000190

Report Number (14) SAND--97-0333C

CONF-9706113--

Publ. Date (11) 199709

Sponsor Code (18) DOE/DP, XF

UC Category (19) UC-700, DOE/ER

DOE