THE ATLAS LOAD PROTECTION SWITCH[*]

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Abstract

Atlas is a high-energy pulsed-power facility under development to study materials properties and hydrodynamics experiments under extreme conditions. Atlas will implode heavy liner loads (m ~ 45 gm) with a peak current of 27-32 MA delivered in 4 μs, and is energized by 96, 240-kV Marx generators storing a total of 23 MJ. A key design requirement for Atlas is obtaining useful data for 95% of all loads installed on the machine. Materials response calculations show current from a prefire can damage the load requiring expensive and time consuming replacement. Therefore, we have incorporated a set of fast-acting mechanical switches in the Atlas design to reduce the probability of a prefire damaging the load. These switches, referred to as the load protection switches, short the load through a very low inductance path during system charge. Once the capacitors have reached full charge, the switches open on a time scale short compared to the bank charge time, allowing current to flow to the load when the trigger pulse is applied. The time window of vulnerability for load damage is thus substantially reduced. The design of the load protection switches and test results are presented.

I. INTRODUCTION

Atlas is a pulsed-power facility under development at Los Alamos National Laboratory to drive high-energy density experiments [1-5]. It is optimized for material properties and hydrodynamic experiments under extreme conditions. The system is designed to implode heavy-liner loads in a z-pinch configuration. The peak current of 27-32 MA is delivered in 4 μs. For many applications the Atlas liner will be a nominal 45-gm-aluminum cylinder with ~ 4-cm radius and 4-cm length (see figure 1). Implosion velocities exceeding 14 km/s are predicted. Using composite layers and a variety of interior target designs, a wide variety of experiments in ~ cm^3 volumes may be performed. These include:

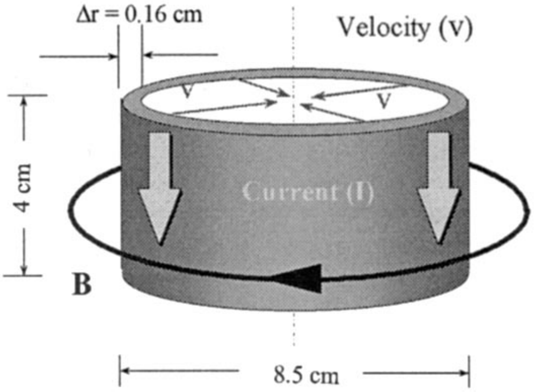

Figure 1. Atlas liner configuration

- high-pressure quasi-adiabatic compressions
- nonlinear and turbulent hydrodynamic instability studies over multi-cm distances
- experiments with dense, strongly coupled plasmas
- studies of material response at very high strains and strain rates
- material studies in ultrahigh magnetic fields (above 10^3 T)
- Magnetized target fusion experiments

Atlas will be operational near the end of 2000 and is designed to provide 100 shots per year.

The Atlas machine configuration is shown in Fig. 2.

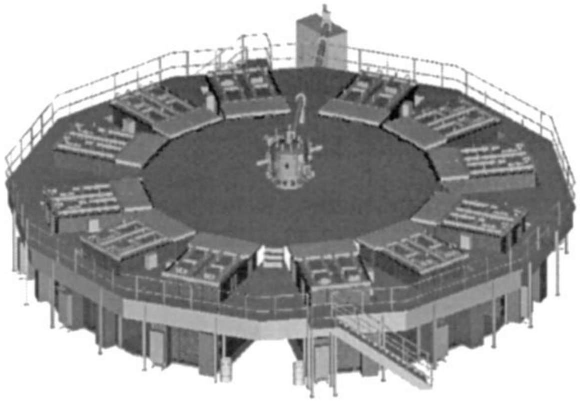

Figure 2. Atlas machine configuration

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The 23 MJ capacitor bank is housed in 12 separate Marx tanks surrounding the target chamber. Each tank contains two, independantly-removeable, maintenance units composed of a set of four Marx modules. The Marx modules have four capacitors charged at up to ± 60 kV and two-railgap switches. When the switches are triggered, the Marx modules erect at up to 240-kV. The output of each maintenance unit is connected to a low inductance, oil-insulated cable header by 56 coaxial cables. The headers provide a means to quickly disconnect the maintenance unit from the rest of the system for servicing. Each cable header is connected by a second set of coaxial cables to the input of the load protection switch (LPS). The fast-acting, mechanical, load-protection switch prevents the load from damage in case of a prefire. A set of 24 tapered, vertically oriented, oil insulated triplate transmission lines transmit the current to a diameter 2.5 m where a transition section couples the current to a solid-dielectric insulated, radial and conical transmission line that delivers current to the load. Figure 3 shows two transmission lines and two maintenance unit tanks. The load is housed in a 1.8-m-diameter, stainless steel, vacuum chamber that provides debris containment and good diagnostic access.

II. LOAD PROTECTION SWITCH

A. Requirements

Atlas design requirements place a high premium on the reliability of each shot. We are requiring 95% of installed loads yield useful data. This requirement is driven by the expense and time required to replace the liner load and power flow channel that will both be destroyed in a firing. The Atlas loads, in particular, are expected to be expensive because of precision machining required to avoid Rayleigh-Taylor instabilities.

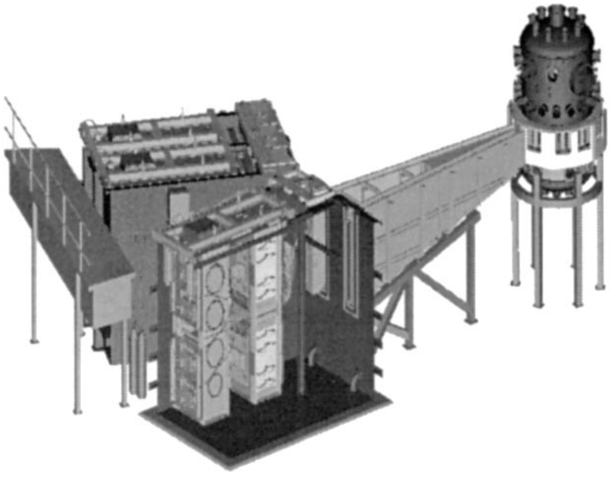

Figure 3. Radial segment of machine

A prefire of a maintenance unit trigger generator during charging is a major concern. Calculations show a typical load will be distorted requiring replacement. Calculations were performed using three-dimensional dynamic material response models of the load using calculated non-axisymmetric current distributions and benchmarked materials models. The prefire rate therefore needs to be a small fraction of the overall failure rate requirement of 5 % (1 % would be desirable). For an estimated prefire rate of 0.33 % for each trigger generator, the overall prefire rate will be 12 % /shot for the full system of 36 master and sub-master trigger generators, exceeding the overall reliability requirement. To reduce this to an acceptable level, we will use a set of fast-acting mechanical switches to reduce the time the load is vulnerable to a prefire from approximately 10 s to 0.25 s giving an additional factor of 40 reduction in the prefire rate to an acceptable value of about 0.3 %.

The load protection switch shorts each maintenance unit through a low inductance path to ground during capacitor charging. In case of a maintenance unit prefire, only ~ 35 kA flows through the load causing no plastic deformation to the load, eliminating costly and time-consuming load replacement. In a normal firing sequence:

1. The capacitors are charged (28 s).
2. All load protection switches are opened (0.25 s).
3. Limit switches on the switches are used to confirm that all switches are open.
4. The machine is fired.

The design requirements for the switches are as follows:

- Normal current: 1.3 MA
- Prefire current: 2.6 MA
- $\int i^2dt$: 1.5×10^7 A^2s
- Peak voltage: 240 kV
- Inductance: < 7.2 nH
- Opening time: < 0.3 s
- Lifetime for normal operation: 1000 shots
- Lifetime for prefire: 25 shots

B. Description

Figure 4 shows the current flow paths in a cross sectional view through the switch, for shorted and open positions. Figure 5 shows cutaway views of the switch both during charge and in the firing positions. A photograph of the switch connected to the cable header and the transmission line is shown in Figure 6.

The switch is approximately 1.5 m long with a 30 cm x 30 cm cross section. The LPS is electrically connected to the cable header through 56, 2.15 m long, RG 220 cables, arranged in two vertical rows, as seen in the bottom of Figure 4. The high-voltage ends of the cables are electrically connected to the high-voltage plate by capturing the center conductor of each cable in a "V-grove". The cable outer conductors are connected to ground by clamping the braid to a set of tubes on the

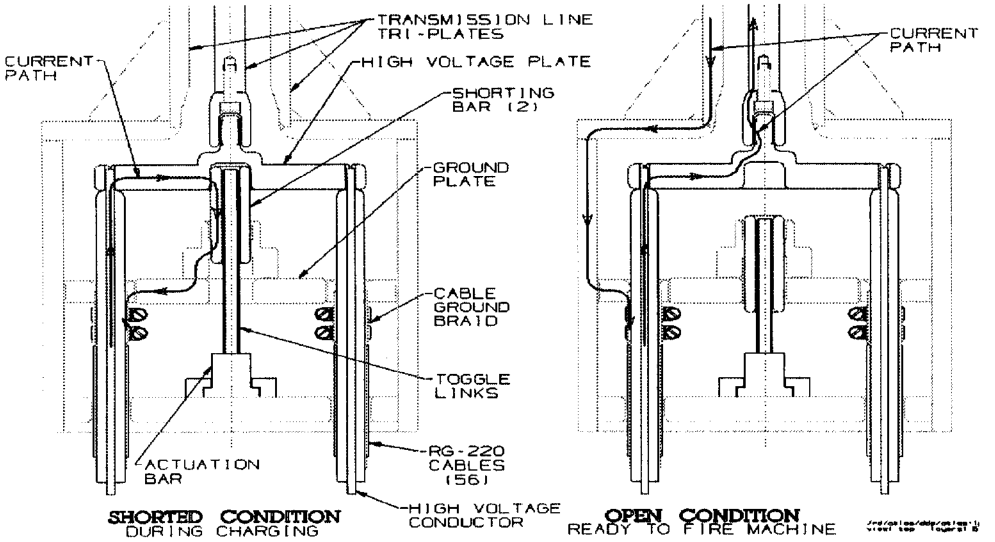

Figure 4. Cross-section of switch with current paths.

ground plates. The high-voltage plate is connected to the center conductor of the tri-plate transmission line by means of a blade that is inserted into a cup in the transmission line center conductor. Two rows of multi-Lam, one on each side of the blade insure good electrical connect (1 kA/louver average current compared to 4 kA/louver surge rating). The electrical connections to the outer conductors of the transmission line are made through bolted current nibs located on the front surfaces of the switch side plates. These nibs make contact with flanges mated to the transmission line outer conductors.

In the shorted position (during charge), the shorting bar bridges the gap between the high-voltage plate and the ground plate, shunting the load. After charge is complete, the actuation bar is driven vertically up by a pneumatic piston operated at up to 100 psi. This drives the four toggle links from horizontal to the 45-deg position pulling the shorting bar into a cup in the ground plate, opening the shunt path across the load. The actuation bar rides on a set of bearings on its rear surface to reduce friction. A position sensitive switch in the piston senses when the switch is fully open. When are switches are open the machine is fired.

C. Mounting Arrangement

The mounting arrangement is shown in Figure 7. The LPS is suspended from the top of the maintenance unit tank on a fixture that allows adjustment in height, tilt and left/right positioning. In addition, the switch moves forward and backward by means of an Acme

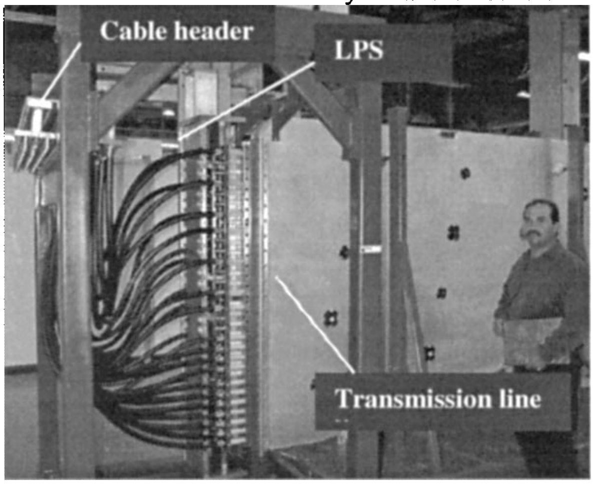

Figure 6. Photograph of the LPS connected to the cable header and transmission line

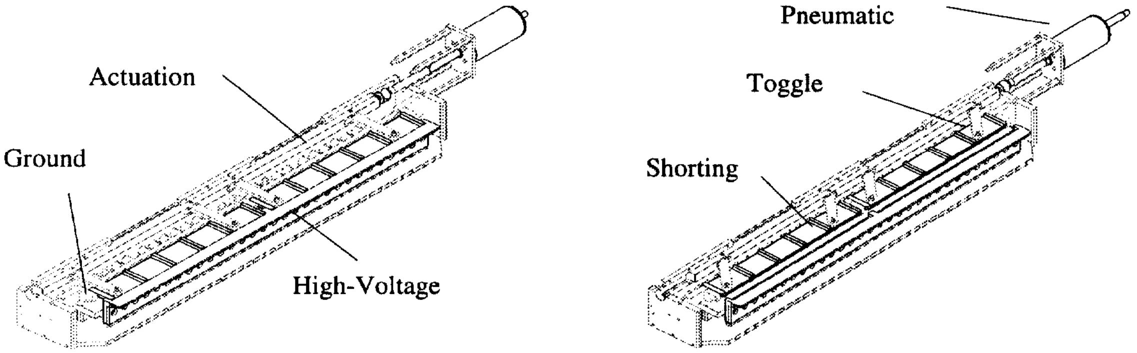

Figure 5. Cutaway view of LPS. Right open position, and left closed

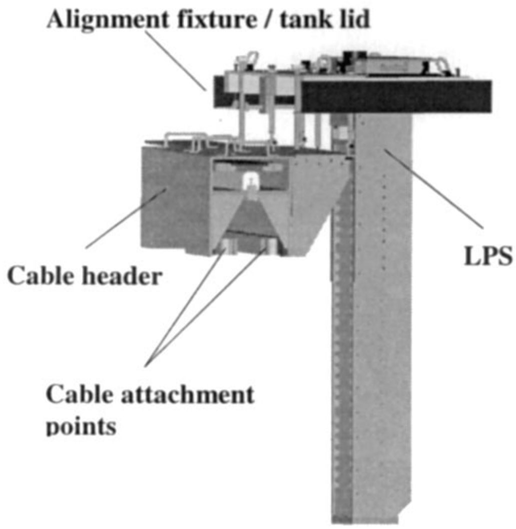

Figure 7. Mounting arrangement for load protection switch.

screw mechanism, on a set of rails, for engagement (and disengagement) into the transmission line. After the switch is engaged, the LPS and transmission line are bolted together from inside the maintenance unit tank. The fixture is also used to support one-half of the cable header and the cables connecting the cable header and LPS. A set of adjustment devices are used to accurately position the LPS half of the cable header so that it mates to the other half on the maintenance unit. Both the LPS and cable header are mounted to the fixture through insulating materials to eliminate ground loops. To disengage a maintenance unit from the machine, the cable header is separated along its midplane and the maintenance unit, with its half of the cable header, is lifted from the tank. The LPS and its half of the cable header can next be removed. Provision is also made to lift the LPS with the transmission line attached to provide the option to mate the LPS to the transmission line before installation. The air cylinder driving the switch is fed through a reservoir located near the cylinder and is connected through large diameter tubing to minimize pressure drops in the feed system.

D. Test results

Mechanical actuation, current joint, and high-voltage tests have been performed on the LPS. The LPS has been mechanically cycled over 2000 times (twice the design requirement) with no significant wear of the moving electrical contacts on the shorting bar. The opening time has been measured to be 0.25 s at 85 psi reservoir pressure (faster than the design requirement of 0.3s) with excellent reproducibility. Current joint tests on the cable center conductor connection and the moving multi-lam contacts on the shorting bar have been performed using test fixtures and a capacitor bank. These were at current densities and actions similar to those expected in the full device under prefire conditions (i.e., at twice the normal current levels). The tests indicate that these current joints will have acceptable wear.

High-voltage tests using a low-current, high-voltage impulse generator have been performed to measure the breakdown voltage of the switch. These results have been analyzed to determine the failure probability of the full array of 24 switches. Two test waveforms were used. Both had a risetime of about 1 μs and exponential decays from the peak. Following reference 6, $t_{eff} = (4/3/V^3_{max}) \int V^3$ had values of 2.05 and 2.75 μs for the two waveforms used. The shorter pulse allowed higher peak voltages to be reached. The voltage waveform at the switch in the final configuration is expected to have a risetime of 0.1μs and $t_{eff} = 0.8$ μs and a peak of at most 240 kV [6]. For the longer pulse, there were 46 shots above 390 kV with 3 breakdowns on the trailing edge of the pulse at $t > 11$ μs. For the shorter pulse there was one breakdown at 10 μs in 18 shots above 470 kV. Using the same type of analysis employed in reference 6, the calculated probability of failure was between 10^{-3} to 10^{-4} for all 24 switches used in parallel. This failure probability meets our requirement. The calculations make the conservative assumption that the breakdown voltage scales as $t_{eff}^{-1/6}$, rather than $t_{eff}^{-1/3}$ generally used for shorter pulses than those considered here.

III. ACKNOWLEDGEMENTS

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