CABLE INSULATION BREAKDOWNS IN THE MODULATOR WITH A SWITCH-MODE HIGH-VOLTAGE POWER SUPPLY*

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Abstract

The Advanced Photon Source modulators are PFN-type pulsers with 40-kV switch-mode charging power supplies (PSs). The PS and the PFN are connected to each other by 18 feet of high-voltage (HV) cable. Another HV cable connects two separate parts of the PFN. The cables are standard 75-kV x-ray cables. All four cable connectors were designed by the PS manufacturer. Both cables were operating at the same voltage level (about 35 kV). The PS's output connector has never failed during five years of operation. One of the other three connectors failed approximately five times more often than the others. In order to resolve the failure problem, a transient analysis was performed for all connectors. It was found that transient voltage in the connector that failed most often was subjected to more high-frequency, high-amplitude AC components than the other three connectors. It was thought that these components caused partial discharge in the connector insulation and led to the insulation breakdown. Modification of the PFN eliminated one HV cable and significantly reduced the AC components during the pulse. A connector with higher partial discharge inception voltage was chosen as a replacement.

THE MODULATOR CIRCUITRY

The modulator power circuitry is shown in Fig. 1.

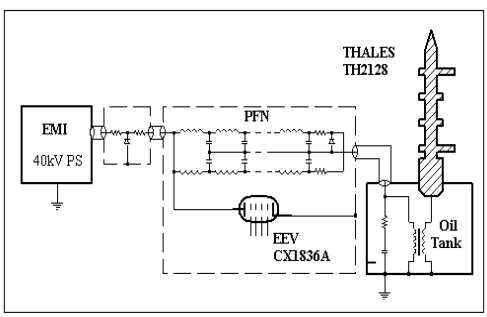

Figure 1: Modulator power circuitry.

The main elements are a 40-kV, 30-kJ/s Lambda-EMI power supply, a 2×8-cell PFN, an EEV thyratron switch, and a 15.3:1 step-up pulse transformer (PT). The charging supply charges the PFN capacitors to up to 40 kV (normal operational voltage is 34 to 36 kV), and then the thyratron switch discharges the PFN into the matched 4-Ω reflected load of the klystron cathode. The process then repeats at a 30 p.p.s. rate. The modulator has a fairly standard design and has been presented at various particle accelerator and power modulator conferences [1- 3].

HIGH-VOLTAGE CABLES

Cable Configuration

The Lambda-EMI PSs have been installed in five operational linac modulators between March 1999 and April 2000. Old PFNs have been utilized in the new modulator design. In addition to the PSs, a copper box with a PS protection circuit (PSPC) consisting of two resistors and a diode stack was placed between the PFN box and the PS (see Fig. 1).

The PS and the PSPC were connected to each other by 18 feet of high-voltage cable (Dielectric Science, model 2060). The PSPC and the PFN were connected by 10 feet of the same cable. Both cables were terminated at the ends with connectors designed by the manufacturer of the PSs (Fig. 2).

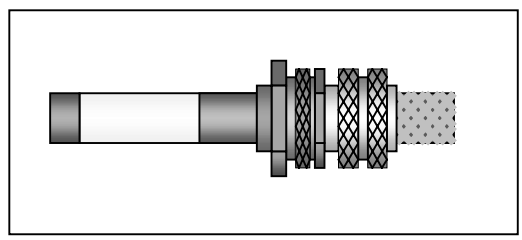

Figure 2: High-voltage cable termination.

Cable Failures

Since the first PS with the PSPC and the cables were installed in 1999, we have experienced 24 connector failures. Failure distribution over the years is presented in Fig. 3.

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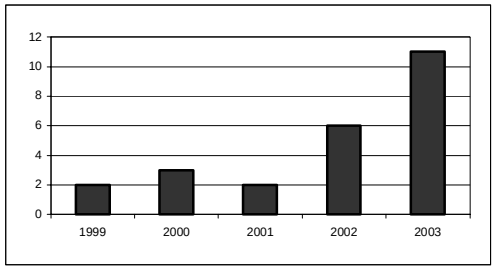

Figure 3: Cable failures per year

All failures were found to be almost identical breakdowns of the cable insulation in the area of the cable braid termination inside the connectors. We believe that increase in the number of failures is related to cable aging and rise of modulator operational voltage.

Connector Failures

The failures were distributed unevenly between four cable connectors (see Fig. 4).

In Figure 4:

- PS – Power Supply connector
- PSPC In – PSPC Input connector
- PSPC Out – PSPC Output connector
- PFN – PFN Input connector

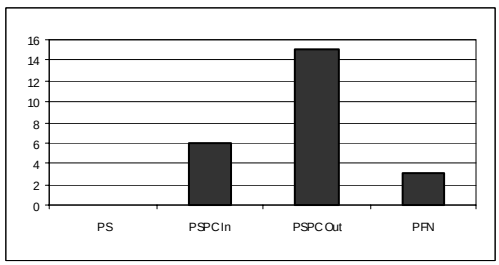

Figure 4: Failures per connector

In order to resolve the problem of such an uneven failure distribution, we performed a transient analysis for all connectors.

Transient Analysis and Direct Measurements

We found that after the thyratron switch closure, transient voltage in the connector that failed most often was subjected to more high-frequency, high-amplitude AC components than the other three connectors (see Figs. 5 though 8).

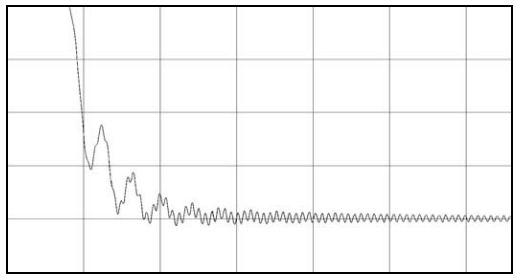

Figure 5: Transient voltage in the PS connector (simulation)

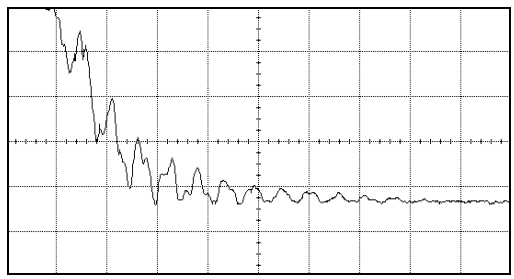

Figure 6: Transient voltage in the PSPC In connector (measured)

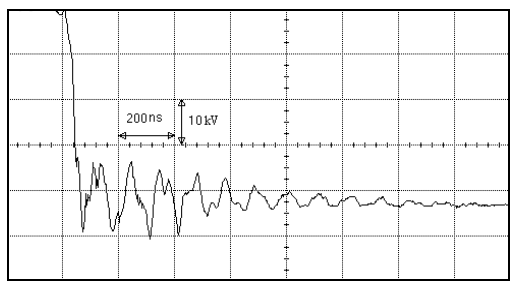

Figure 7: Transient voltage in the PSPC Out connector (measured)

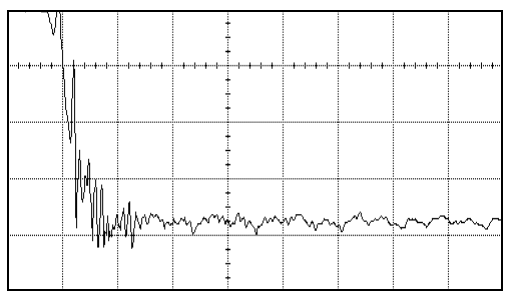

Figure 8: Transient voltage in the PFN connector (measured)

AC components in these plots have frequency of 5 to 10 MHz. It can be seen that the PSPC Output connector is the only one where voltage gets reversed a number of times during the pulse. Maximum reversed voltage in Fig. 8 is about 10 kV peak. We think that this voltage component causes partial discharge in the connector insulation and leads to the insulation breakdown.

MODULATOR MODIFICATION

We considered several different ways to modify the modulator in order to reduce or eliminate high-frequency oscillation in the connectors during the pulse and decided to perform two major modifications at the same time:

- Place the PSPC and the PFN with the thyratron switch in one copper-shielded compartment. This would eliminate one of the two HV cables and two of the four connectors (including the one that failed more often than the others) and reduce AC component amplitude during the pulse.
- Choose another HV connector with higher partial discharge inception voltage as a replacement for one of the two remaining HV connectors.

After major mechanical modulator modifications were complete, a number of different HV connectors with various cables were measured in order to find the connector-cable combination with highest partial-discharge inception voltage. It was found that the Isolation Product connector, model D-102-4, with a Dielectric Science 100-kV x-ray cable, model 2212, was the most suitable combination for this application.

The modifications that had been made to the modulators resulted in elimination of two connectors with the highest reversed voltage value and dV/dt during the pulse (Figs. 7 and 8). The AC component of the transient voltage in the PSPC Input connector has become much smaller (compare Fig. 6 and Fig. 9).

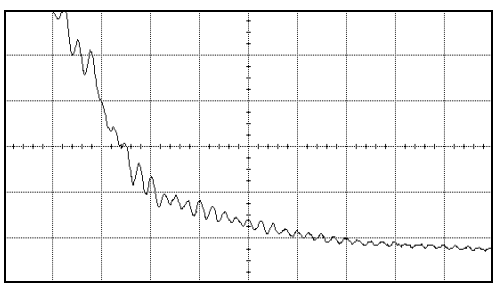

Figure 9: Transient voltage across PSPC Input connector after modulator modification (measured)

In order to make this transient voltage even smoother, a 1.2-nF capacitor was connected in parallel with the connector. Transient voltage across the connector with the capacitor is presented in Fig. 10.

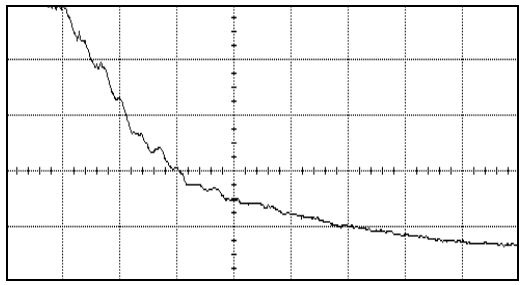

Figure 10: Transient voltage across PSPC Input connector with 1.2-nF capacitor (measured)

SUMMARY

The modulator modifications were completed for most of the APS linac modulators at the end of 2003 and the beginning of 2004. As a result, there have been no connector failures during first seven months of 2004 (see Fig. 11). Modification of other modulators will be completed in 2004.

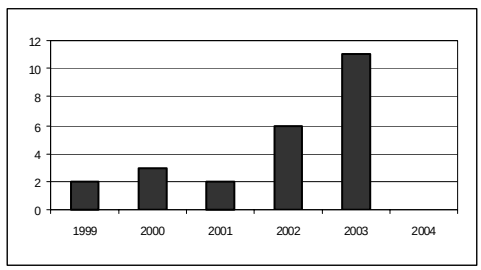

Figure 11: Cable failures per year including 2004

ACKNOWLEDGEMENTS

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[3] A. Cours, T. Smith, "The Advanced Photon Source Linac Modulators. PSpice Simulation and Upgrade", Proc. Twenty-Fifth International Power Modulator Symposium and 2002 High-Voltage Workshop, p. 270, 2002.