Improved High Voltage Coax for Antiproton Source Kicker Pulse Forming Networks and Pulse Transmission

J. Petter
Fermi National Accelerator Laboratory*

Abstract

The Fermilab Antiproton Source has five kicker systems which use RG-220 type, 50 Ohm coaxial cable for pulse forming networks (PFN's) and pulse transmission. These systems include 40 PFN's that run at about 65 kV and 80 transmission cables which carry 32 kV pulses. The cable was breaking down at a rate of about 1 every 2 weeks. The result of a study into these failures showed that the polyethylene breakdown was preceded by a phenomena called treeing. An investigation into this lead to a new cable specification. This article will describe the failures and explain the reasoning behind the specification.

Introduction

In the Antiproton Source application at Fermilab RG-220/U type cable is generally used to form and transmit pulses for our fast pulsed kicker magnets. Referring to figure 1, the DC power supply is ramped up to 65 kV in 500 mS, after a 100 mS delay the thyratron is fired. This creates a pulse traveling down the transmission cables through the magnet to the load that is 32.5 kV in amplitude and 1.6 uS in duration with rise and fall times of about 40 nS [8],[9].

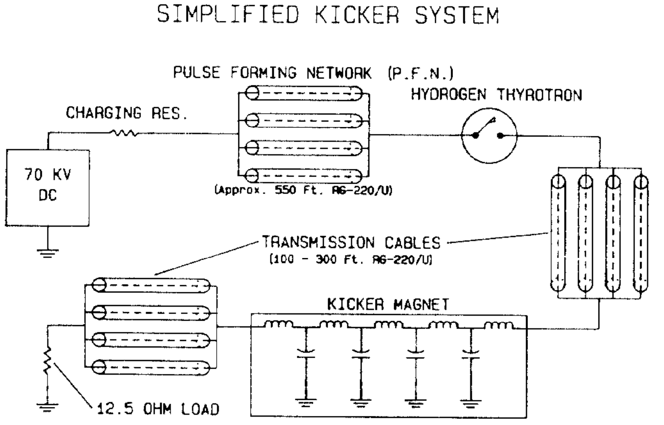

Figure 1

A total of 22,000 ft. of PFN cable (40 PFN's) and 12,000 ft. of transmission cable (80 pieces) are used. About 80% of this cable is cycled every 2.6 seconds. Between the dates 7-2-85 and 2-17-89, 23 PFN's and 23 transmission cables failed.

Some PFN's were expected to fail, but not in such large numbers. We had installed cable with 3 different specifications: RG-220/U type with no other specification (generic), U. S. military specification MIL-C-17/81C [7],[10] (mil. spec.), and an RG-220/U special (special) for high frequency pulse applications. All original PFN's were the generic cable. The first 9 PFN failures were replaced with this same cable. Of the last 14 PFN failures 2 were replaced with the special cable and 12 were replace with the mil. spec. cable. Of these later replacements 1 of each type failed. The other 21 failures where the generic cable. Figure 2 shows the PFN failure rates and a best guess of PFN usage.

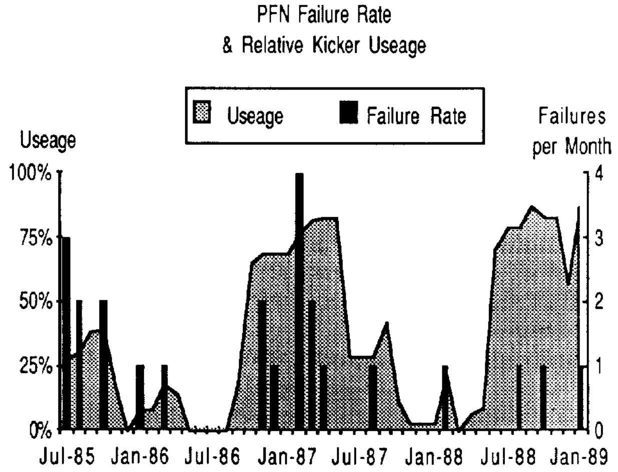

FIGURE 2

The transmission cable failures were a surprise because they only see half the voltage. The original installation of cable was the generic type. The transmission cables were installed by pulling them from the service buildings through the penetrations to the kickers in the tunnel. All the transmission cable failures occurred in the portion of the cable that was pulled through the penetrations. As a quick solution in December of 1986 all transmission cables were replaced with carefully installed mil. spec. cables. For a longer term solution we began an investigation into the cause of the failures with a goal of writing a cable specification for new PFN's. Since the replacement of all transmission cables with mil. spec. cables in Dec. 1986 no additional failures of transmission cables have occurred.

Many tests were performed on the RG-220 type cables. We had samples of unused cable from all 3 types. Unfortunately, failed cable samples were available only in the generic type.

Visual Inspection

The visual inspection of the cables included cutting apart the samples and examining the jacket, braid, dielectric and center conductor. The dielectric was checked for contamination by heating it with hot air until it became transparent. The dielectric was also sliced and examined under a microscope.

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The special cable had no visual problems. The braid and jacket seemed to be tighter around the dielectric than the others.

The mil. spec. cable had two questionable observations: one sample of cable had water in the braid, all samples had a thin layer of dust in the dielectric, as if they had been extruded in two layers. The manufacture verified that the cable is extruded in two layers and no special care is taken to insure that the cable stays clean between extrusions.

The generic cable had many visible problems. There where many places where the jacket had lumps in it. Under the jacket the braid was very poorly spliced or knotted. In one place the braid coverage was found to be down to about 50%, clear plastic tape was wrapped around the braid and the jacket was applied over the whole mess. The dielectric was full of very large contaminates, some larger than 30 mils! The center conductor was not in the center of the dielectric, and its surface was rough and discolored by corrosion. The used samples of this cable showed the same problems. In addition, bubbles had formed around the center conductor. The cables that where once used as transmission cables had the largest bubbles, as large as 0.1 inches. The samples taken from failed PFN's had fewer and smaller bubbles, barely visible through the hot polyethylene. The larger bubbles and large number of transmission cable failures are assumed to be a result of mishandling when the cable were pulled through the penetrations.

Measurements

The electrical measurements made on these cables included Corona measurements and 60 Hz life tests.

Corona extinction and inception voltages [5],[6] were measured at sensitivity levels of 5, 15 and 30 picocoulombs. These corona measurements were made on 5 ft. pieces of both braided and unbraided cable. The findings in general were as follows:

The braided cable inception and extinction measurements showed the special cable to be slightly better then the others (23 kV vs. 20 kV). The cables that had been cut from failed PFN's were slightly worse but still better than 14 kV as required by the military specification. The cables that had been used as transmission cable were lower still around 10 kV. Inception was always slightly higher than extinction except on the very poor cables. Inception and extinction voltages were insensitive to sensitivity level within 2 or 3 kV. Extinction voltage rose 2 to 7 kV after stressing the cables for 30 minutes at 35 kV. Removing the braid caused the extinction voltage to raise 0 to 17 kV.

The 60 Hz life tests were done on unbraided cables at 50 kV rms. The time to failure was measured, two transmission cables were tested, one failed immediately, the other failed after 5 hours. The two PFN's tested failed after 9 and 11 hours. One new piece of generic cable was tested, it failed after 204 hours. Two pieces of the mil. spec. cable were tested, neither failed after 241 and 265 hours.

Trees

It was suggested that our problem may be Treeing. A comprehensive description and summary of work on treeing has been written by Eichhorn [2],[4].

Treeing is a prebreakdown phenomenon. The term is applied to the type of damage that progresses through a dielectric under electrical stress that when visible resembles a tree. Treeing initiates at a point of high divergent electric field. Trees have been observed to grow in a-c and d-c fields and under impulse conditions. Trees may occur more rapidly as a result of impulse voltages. It is important to point out that in solid organic dielectrics, treeing is the most likely mechanism of electrical failures which do not occur immediately but seem to be the result of an aging process. [4]

Electrical tree growth slows if trees are not vented. The theory is that pressure built up in the voids due to ionization causes the ionization to cease until the pressure reduces. This theory can be used to explain the fact that the measured extinction voltage rose after running the cable at 35 kV for 30 minutes. This theory could also be used to explain why our cable failures were concentrated at the ends. A PFN is 550 ft. long. 17.4% (4 of 23) of the failures occurred within the 3.6% of the cable that is within 10 ft of an end. It seemed likely that treeing was the problem, but the only way to be sure was to find a tree.

Many hours were spent looking at 30 mil thick cross sections of cable under a microscope. Staining techniques [3] and different lighting were tried, but nothing was found which was clearly a tree. This is a very time consuming method of looking for trees, the author recommends avoiding it if possible.

If there are trees in a piece of cable, they must be the weak points. 100 kV d-c was applied to 12 ft. pieces of cable, hoping they would break down at a tree. Nothing happened. It was realized that trees could be located using the 60 Hz life tests. A circuit was design to turn off the high voltage within one a-c cycle when a failure occurred. It was hoped that if there was a tree at the point of breakdown one arc would not be enough to destroy it. The result was 5 breakdowns and 4 trees. When the cables failed the burnt material stained the trees very nicely.

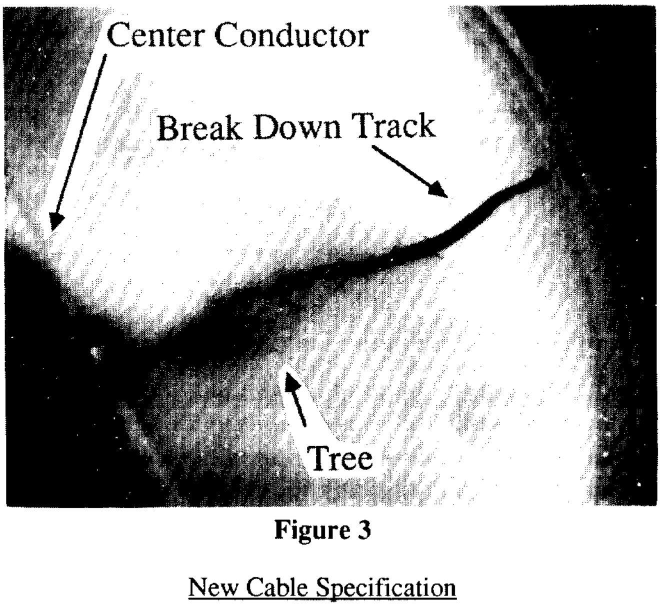

Figure 3

New Cable Specification

Based on the knowledge gained in this cable failure study a cable specification was written. Cable was ordered to replace all PFN's and transmission cables. The resulting specification [11] was the same as MIL-C-17/81C except for the items listed on the next page:

- Insulation must be extruded in a single pass unless it can be proven that the cable is kept clean between extrusions.
- Tree retardant thermoplastic polyethylene was required. The author knows of only one source of this material, Union Carbide Corp. TR-6202. Unfortunately they no longer make this material. A possible substitute is a crosslinked tree retardant polyethylene. Crosslinked polyethylenes can have better tree retardant characteristics, but there is some question about there high frequency losses. Also the curing process makes cables more expensive to manufacture.
- Void and contaminant measurement of samples under a microscope.
- No maximum adhesion limit of the center conductor to the polyethylene. The military specification has an upper limit for stripablity reasons.
- A longitudinal aluminum tape shield was bonded to the cable core under the braid to help with the high frequency shielding. This makes the attenuation better and helps to stop corona in the outer conductor.
- Corona extinction voltage was changed to 25 kV at 15 pC from 14 kV at 5 pC. Extinction voltage is required to be measured on every full length of cable, not just samples. The manufacture had some trouble meeting this specification so we had to accept some cables with extinction levels between 20 and 25 kV to be used as transmission cables. It is believed that most of the corona problems were due to small wrinkles in the aluminum tape. One solution to this problem is to do the corona measurements before the braid is applied.

Comments

Military grade RG-220 has been used in the past for applications similar to our application. It has preformed satisfactorily with few failures. The generic cable used more recently failed at a very unsatisfactory rate. Most of the samples of generic cable we examined would probably pass MIL-C-17/81C. For this reason the author believes that the military specification is not adequate to guaranty reliable operation in our application. We have been getting satisfactory reliability only because the cable we have been receiving surpasses military specifications.

The author believes that it is extremely hard to make a cable of this design that does not have some corona at our operating voltage of 65 kV. 65 kV corresponds to a corona level of 46 kV rms. Thus, most cables in our system should fail eventually due to treeing. The time to failure can be increased by as much as 10 times if tree retardant polyethylene is used.

In our case low loss and cable size restrictions limited the design. Without one or both of these limitations the following things should be considered for either more reliable or higher voltage operation:

- A semiconductive polyethylene layer around the center conductor to get a better interface between conductor and dielectric, thus reducing corona.
- A larger cable.
- Crosslinked polyethylene for greater tree resistance.
- Semiconductive layer around the outer conductor to reduce corona there.
- Make corona measurements on the cable core, without an outer conductor, since the center conductor corona is much more likely to contribute to the eventual failure.

Conclusions

The failure mechanism in our case was treeing brought about by and enhanced by poor quality cable and in the case of our transmission cables poor handling during installation. From the investigation into these failures the things we learned where not at all surprising.

It is known that electrical breakdown always starts in regions of the largest and most divergent electric stress. Thus, any means to maximize field uniformity and minimize field strength is good. Dielectrics must be isotropic and uniform down to microscopic levels. Testing of all full lengths of cable for corona can help weed out bad spots but is no substitute for a good design and careful manufacturing.

After the above has been accomplished the life of a good high voltage cable design can be enhanced by using a tree retardant dielectric.

On 12-23-88, 15 PFN's were replaced with the new cable. And on 2-8-89, 12 more PFN's were replaced. They have all been on a 2.6 second cycle since their installation. No failures have occurred as of 3-10-89. After the original installation, 5 cables had failed by the time there where as many PFN cycles. There isn't enough time on the new PFN's to claim success, but there is enough time to claim an improvement over the original cable.

Acknowledgements

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