The Partial Discharge Tests of the High-Voltage Cables and Other Components at the APS

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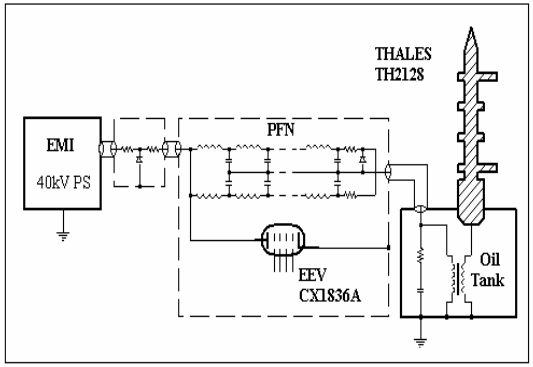
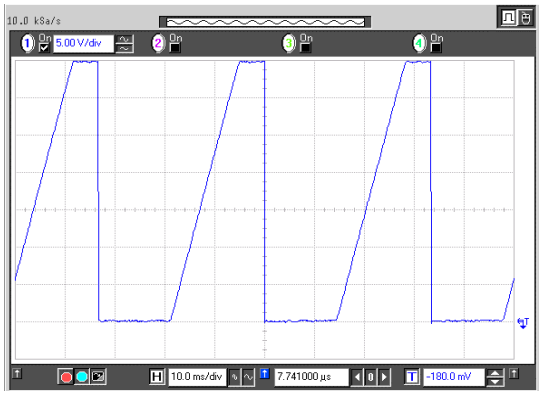
A U.S. Department of Energy laboratory managed by The University of Chicago

Presentation Content

- **Part I – The Advanced Photon Source (APS) Linac modulator cable characterization.**
- **Part II – The design and testing of HV cables for the APS particle accumulator ring (PAR) kicker magnet upgrade project.**

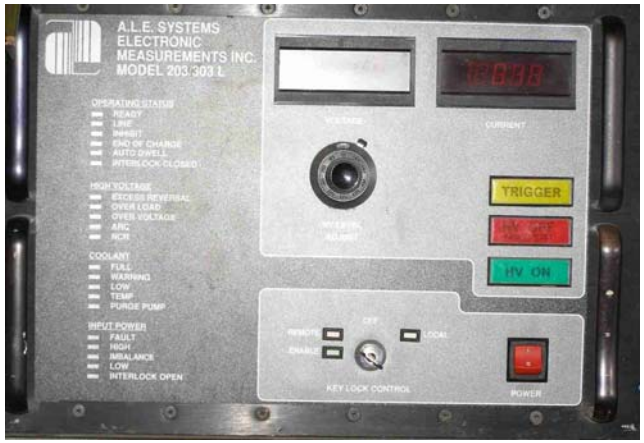
Part I - Introduction





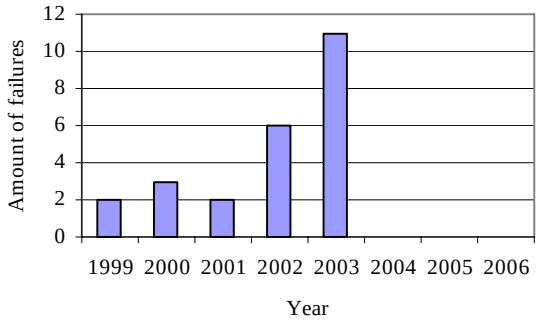
- The APS Linac modulators are conventional design PFN-type pulsers with 40-kV switch-mode charging power supplies (PSs).
- The modulators produce cathode voltage pulses (5-µs, up to 312 kV) for the 35/45-MW Thales TH2128 (TH2128D) klystrons. Pulse repetition rate is 30 p.p.s.
- 75-kV standard x-ray cables were connecting the PSs and PFNs.
- The typical operation cycle of the modulator includes a 10-13-ms dwelling period, 15-ms linear charging up to 40 kV (a typical operating level is 34 to 36 kV), and a few millisecond long pulse waiting time.
- Each modulator produces over 600 millions of 65 to 70 MW pulses per year.

The EMI Charging Power Supply and Connector 1



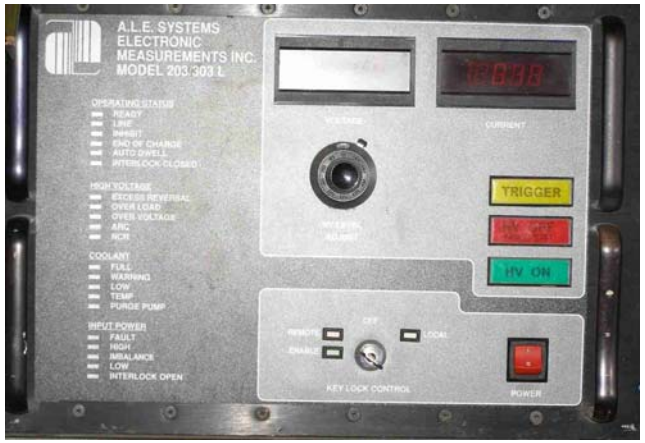
- The EMI 40-kV constant current HVPS is used to charge the modulator PFN.
- Average charging current is 0.7 - 0.8 Amps.
- One particular feature of the supply makes our life a little more difficult (will tell in a couple of minutes…).

HV Cable Failures 1

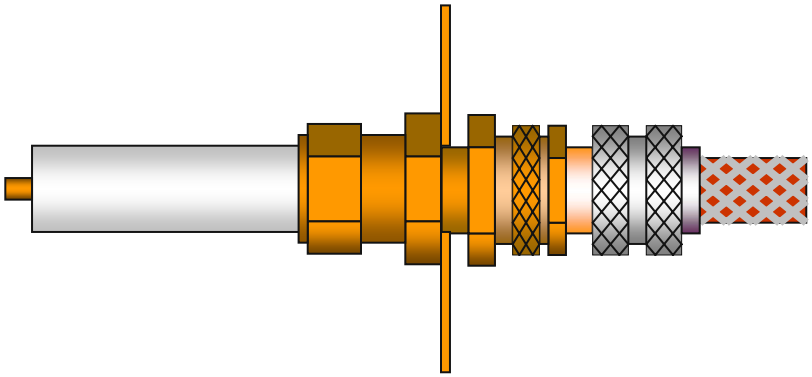


- At some point amount of breakdowns in the Linac modulator HV cables (rated at that time 75 kV dc) started to grow.
- Type of the damages indicated that they were caused by partial discharge (PD) activity in the cable connectors.

The EMI Charging Power Supply and Connector 2

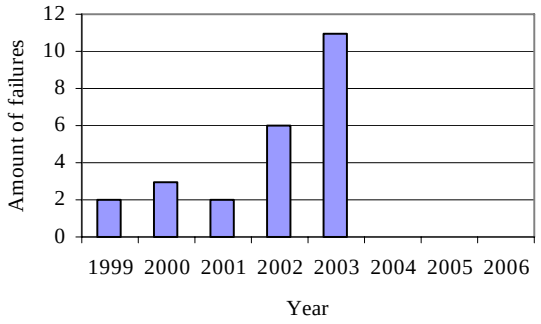


- The EMI 40-kV PS forces us to use a specific type of HV connector that cannot be replaced by another type since a part of it is located inside the densely packed PS.
- This connector is unique because of its main parts: the body, feed through, insert, etc., are commercially available from companies that produce… plumbing components.



- One of the parts: the “reducer”.

HV Cable Failures 2



- At some point amount of breakdowns in the Linac modulator HV cables (rated at that time 75 kV dc) started to grow.
- Type of the damages indicated that they were caused by partial discharge (PD) activity in the cable connectors.
- A cable with higher operating voltage (100 kV dc) and more reliable connectors were chosen to replace the old ones.
- During the year of 2004 all old cables were replaced, and the modulators were modified in order to reduce amount of cables and eliminate voltage reversal and high frequency oscillations in the cable connectors.
- No cable failures have happened since then.

Concerns Related to the Modulator Cables

- We have a broad experience of the modulator cable failures and learned that:
  - troubleshooting the failures involves electrical shock and arc flash hazards;
  - replacing the cables is a time consuming process affecting the overall APS reliability statistics;
  - cable breakdowns may also damage the expensive EMI HV power supplies.
- First PD tests of the new cables were upsetting:
  - PD inception voltage (PDIV) measured in some of the cables was only 20-21 kV ac which corresponds to 28.2-29.6 kV peak, while peak level of the PFN voltage may reach 40 kV (normal operating level is: 34-36 kV);
  - It may mean that over the time, PD currents will cause deterioration of the cable insulation, and eventually result in the cable breakdown.
- In order to monitor condition of the insulation and determine time when the cables need to be replaced, we started to perform PD tests on a regular basis.

AC Dielectric Test Set

- An AC dielectric test set (the Set) with a PD detector was installed and commissioned at the APS in January 2005.
- The Set has output rating of 40 kV ac, 75 mA.
- The Set is used on a regular basis for the following purposes:

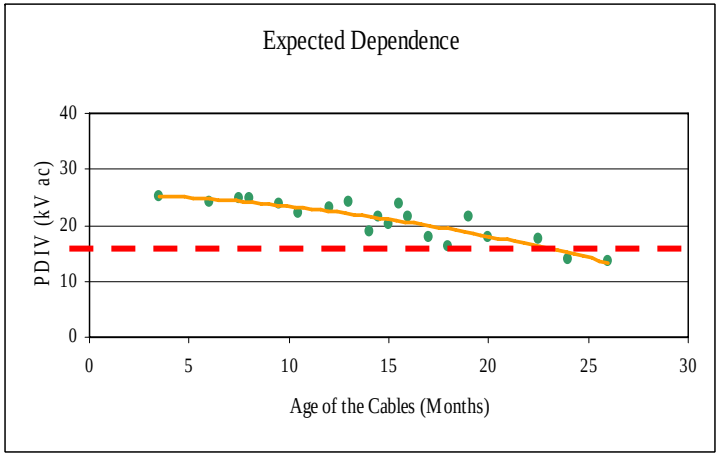
AC Dielectric Test Set

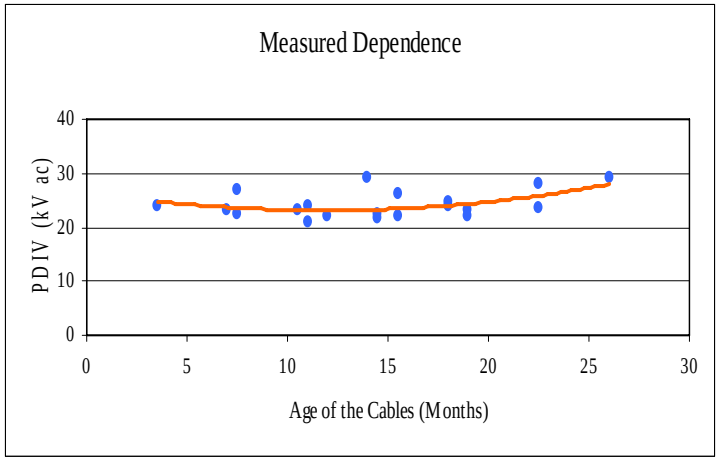
- Early detection of high-voltage (HV) cable insulation degradation and cable breakdown preventive maintenance.
- Characterization of various HV connector types and selection of those with the highest PD inception voltage and lowest PD current values.
- Testing various greasing and insulating materials and techniques.

PDIVs vs. Age of the Modulator Cables

- When we began to perform regular cable PD tests, we expected to see something similar to the plot on the right (not real, just an example!), where each dot would represent PDIV of a cable with a particular age. And if PDIV of any cable falls below some minimal tolerable level, the cable would be immediately replaced ensuring failure preventive maintenance.

- Reality turned to be quite different: no evidence of aging of the insulation in any of the five modulator cables that are regularly tested was observed. What is more, some positive trend may be seen.





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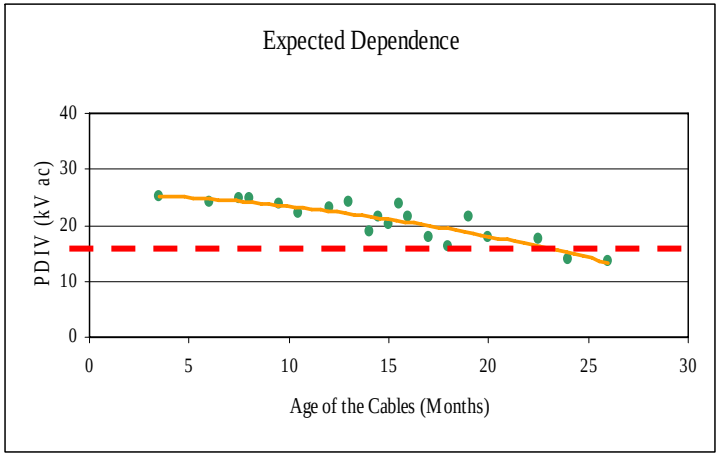
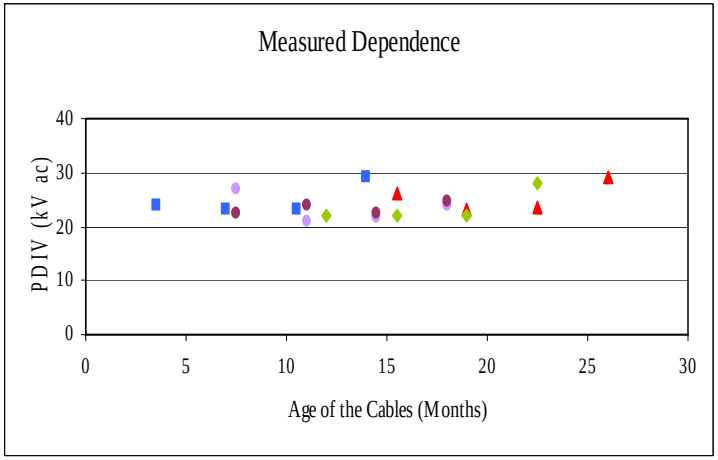
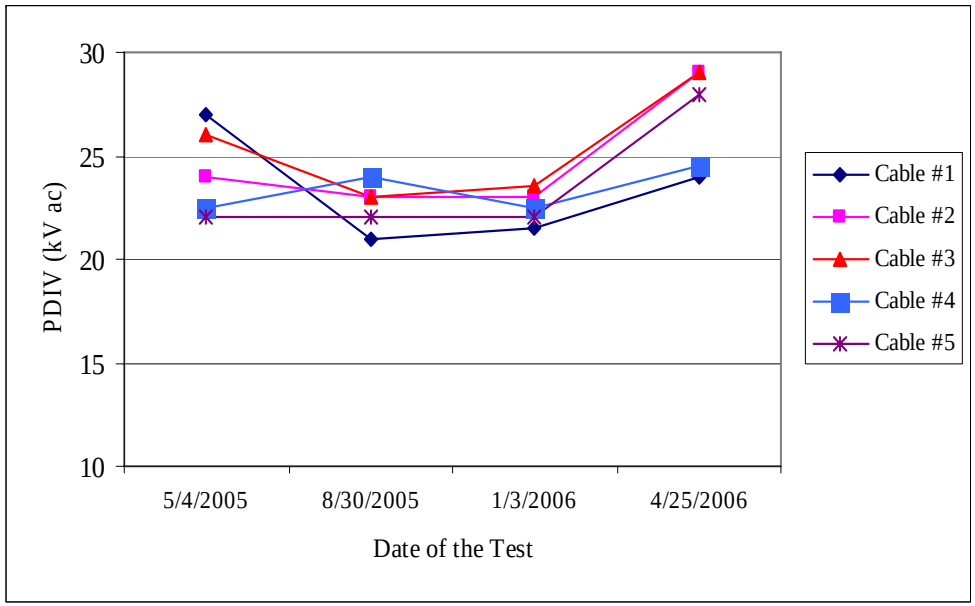


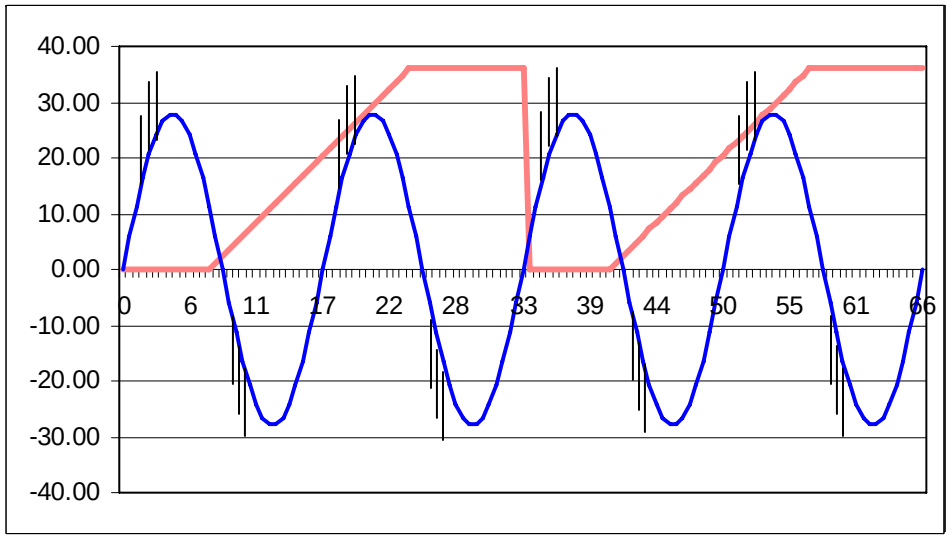


PDIVs in the Modulator Cables



- Lines on this plot represent PDIVs in the individual cables measured during four consecutive tests over the last year.
- Direct interpretation of the curves is a difficult task:
  - there is no evidence of insulation aging in any particular cable;
  - results of a particular test seems to depend on who and how accurately prepares the cables for testing.

Applicability of the Method



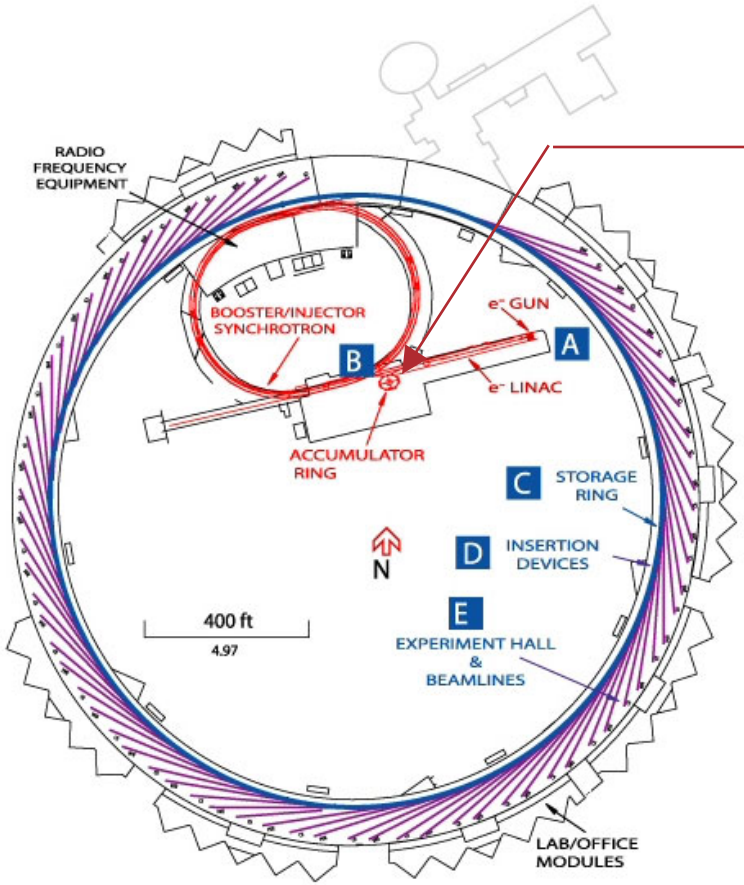
- A 60-Hz HV is applied to the device under test (DUT) during PD measurements
- At some voltage level PD pulses appear on the detector screen. We record this level as the PDIV.
- What can we say about PD in the device when we apply real voltage of this kind which is so much different from the test signal?

- Do we really need to try to have cables or other HV devices that are PD-free up to the operational voltage level?
- Maybe 21-kV PDIV measured in our cables is good enough for reliable work with 36-kV peak level of the real signal?

Part I - Conclusion

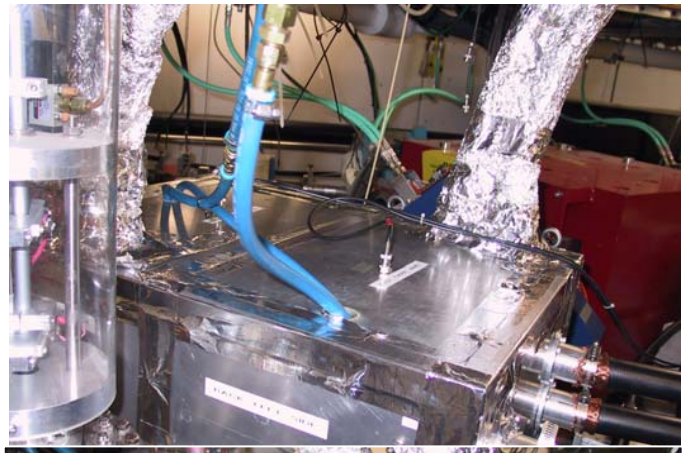
- **The PD test results that were received over the last year make us believe that:**
  - **The HV cables that are used in the APS Linac modulators can survive during many months under existing conditions w/o noticeable deterioration, despite the fact that the peak operational voltage of the cables significantly exceeds peak value of the PDIV measured during the standard PD tests.**
  - **PD test results depend on cable preparation process. It also convinces us that proper handling of the cables plays one of the major roles in extending life time of the cables.**
  - **It is worth to continue regular PD measurements in the future.**

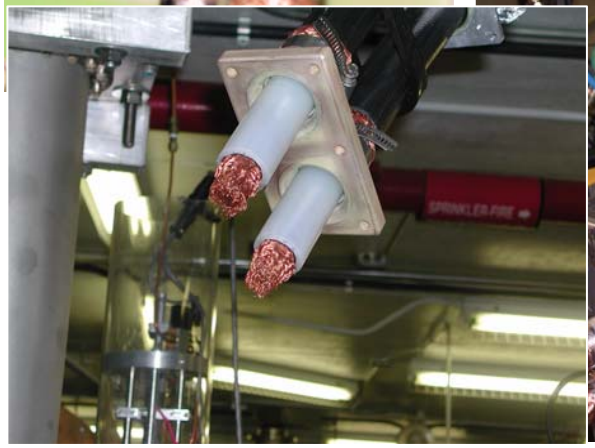
Part II - Introduction

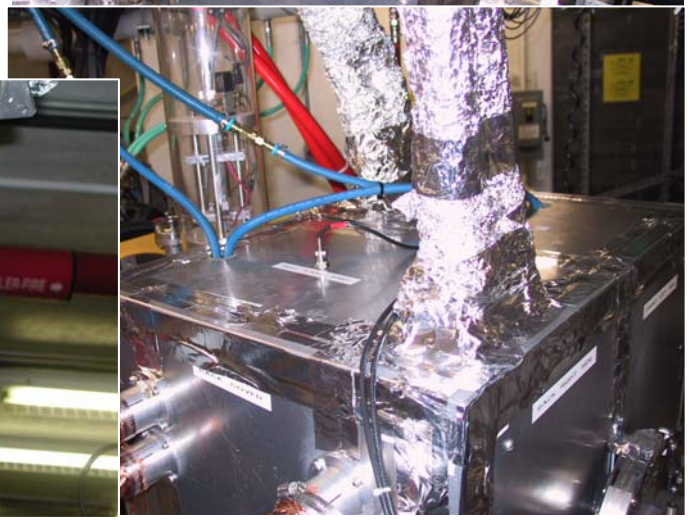


- The APS particle accumulator ring (PAR) is a 325-MeV storage ring that collects and compresses linac pulse trains into a single bunch for booster injection. The cycle time of the PAR is 500 ms.
- Three fast kicker units are required in the PAR. Two of them for both beam injection and extraction. The third unit is required for beam extraction only.
- The kicker magnets produce short pulses of magnetic field with the field strengths of several hundred Gauss with repetition rate of 12 to 30 p.p.s depending on the operational mode of the linac (for injection), and 2 p.p.s. (for extraction).
- Operating voltage level on the kicker PFN is 35 kV (design goal).

High Voltage Cables – The Starting Point







- Cables as we used them in the original PAR kicker design.

  Model: Times AA7949 (Belden YR-10914), 14 Ohms.

- As many as twelve cables failed over the last 12 years.

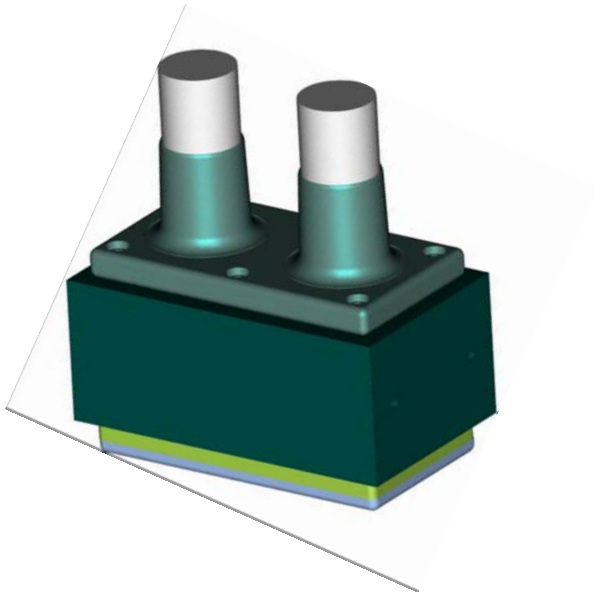
- The cables are inflexible and very hard to handle.

The PAR Kicker Upgrade Project

- The APS PAR kicker magnet upgrade project is close to completion.
- As a part of the project, the new PFN cable assemblies were designed and tested.
- The goals of the cable design are:
  - Reliable at 35 kV (PD-free);
  - Easy to Repair / Plug & Play;
  - Improve manufacturing process;
  - Attention to details in terminating PFN cables to reduce failure rates;
  - Testing:
    - Partial discharge to 40 kV and < 50 pC,
    - HiPot testing to 70 kV and < 30 mA for 30 min.

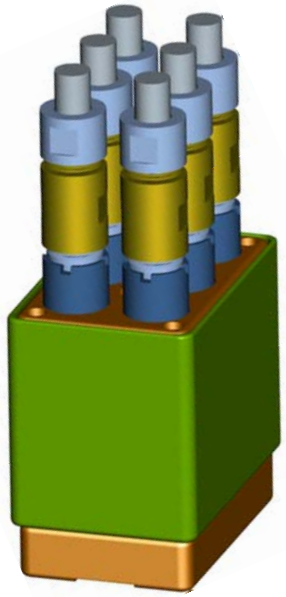
Cable Termination

- **Original Design**



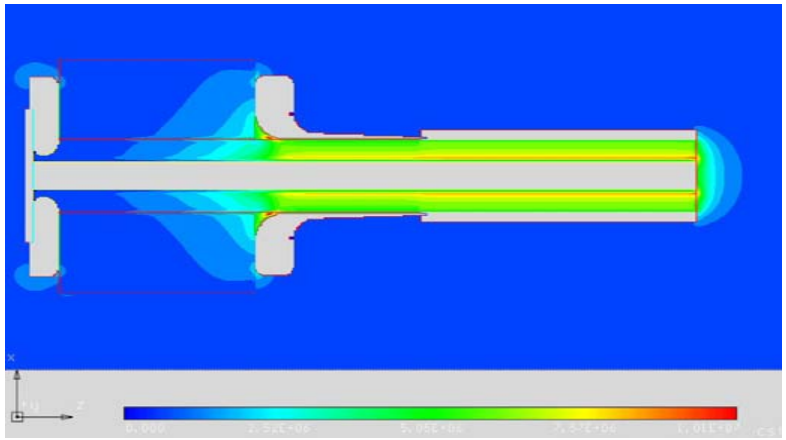
- **Disassembly of the G10 block and part of the magnet is required to replace one or both cables**

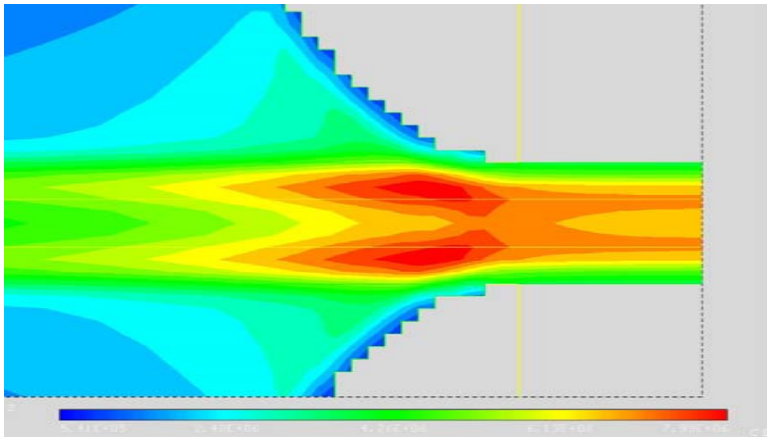
- **New Design (uses a plug receptacle system)**



  - **Dielectric Science cable Model: DS-2214**
    - **Flexible.**
    - **Easier to handle.**
    - **But 50 ohm impedance (6 cables in parallel).**

High Voltage Stress Analysis





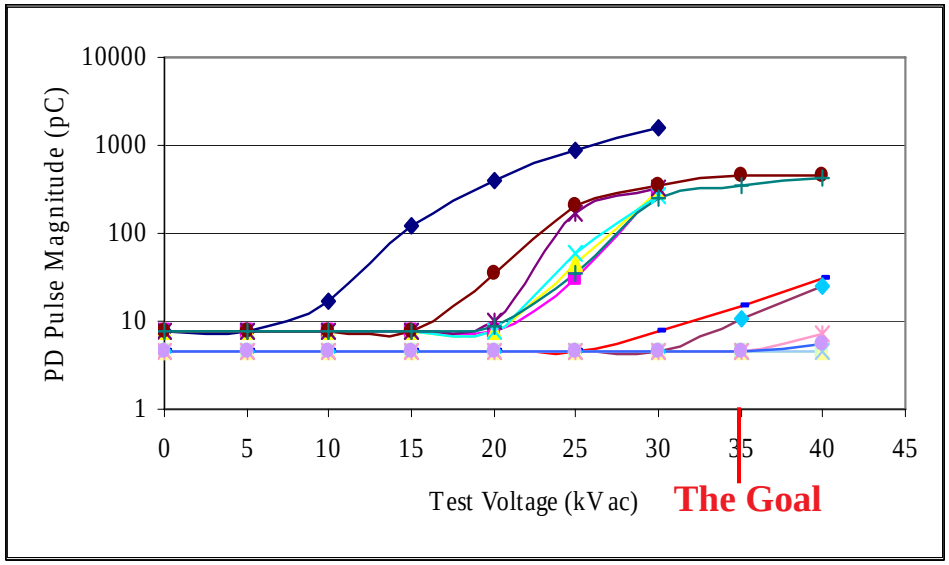
- **Prior to the cable manufacturing, the HV stress analysis was performed by Geoff Waldschmidt of the APS/ASD-RF Group for the old and new termination designs. The simulation results indicate significant drop of the peak field level inside the new connector in comparison with the old one:**

Peak Field (Original Design):		Peak Field (New Design):
13.8 MV/m at 35 kV	⟷	8.2 MV/m at 35 kV
(7.9 MV/m) at 20 kV		(4.7 MV/m at 20 kV)

Kicker PFN Cable Assembly at the PD Test Set

- **Here is a complete PAR kicker PFN cable assembly ready for testing with the PD test set.**

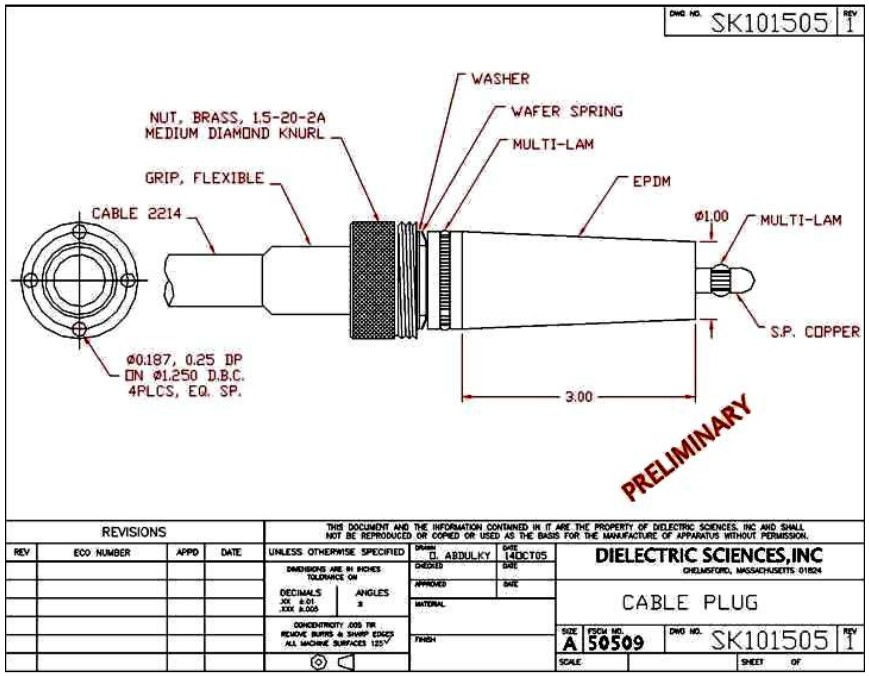
PAR Kicker Cables – Test Results

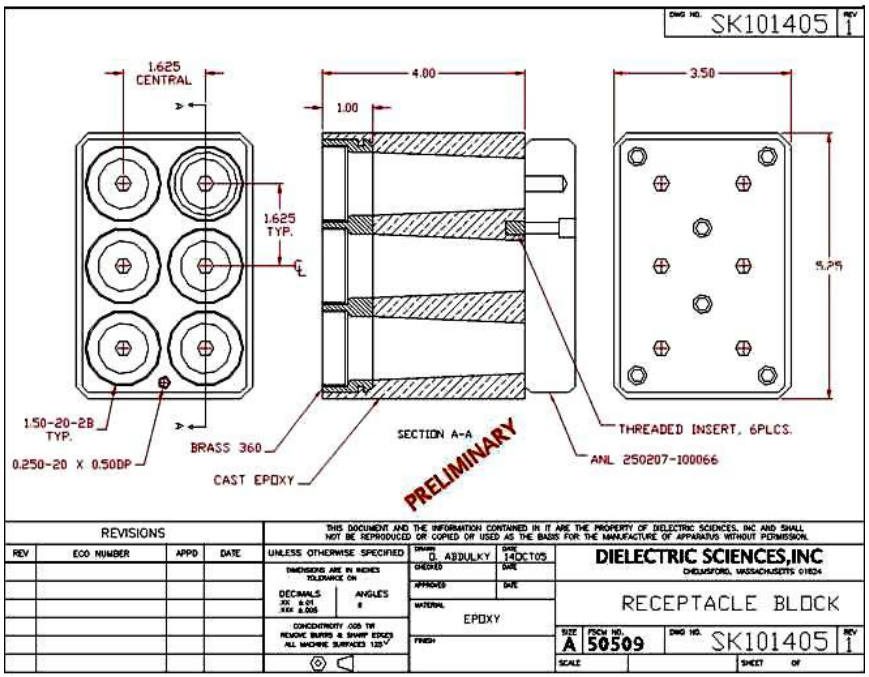


- The first prototype cable had a very low PDIV and extremely high magnitude of the PD pulses.
- The next three prototype- and several revised-design cables were better but still far from the design goals.
- Cables that were built after the second revision have shown even greater results, but in order to meet our goals we continued improving the cable termination design and assembly technique.

- The final version of the cable completely meets and even exceeds the design goals, and will be used when new PAR kicker magnets are manufactured.

PAR Cable – Final Version





- One full set of the cables (6) has been assembled and tested by now. All cables meet specification.

HV Stand-off

- **New design testing for PDIV:**
  - **we have successfully tested up to 40 kV ac with < 20 pC on first articles;**
  - ***we have noted that the cleaning, handling and assembly process play are major contributors to the success of the testing;***
- **New design HiPot Testing to 70 kV**
  - **we have tested to 70 kV dc for a period of 30 minutes;**
  - **but we have also had breakdown inside the prototype connectors in cases when grease was poorly applied in the connector.**
- ***AND…***

Cable Assembly

- **The PAR kicker cable assembly process now looks like this…**

High Voltage Safety

- **Working with High Voltage Safety is extremely important.**
- **Proper PPE must be worn ant all times.**
- **Have a detailed safety procedure with you.**

- **The measurement and controlled discharge of stored energy must be followed.**

Conclusion

- **The APS PD test set is a very effective instrument that has been helping us successfully perform various tasks:**
  - **Characterize various cables, connectors, greases and assembly techniques,**
  - **Ensure preventive maintenance of the existing equipment,**
  - **Design cable assemblies and other parts that perfectly meet new design goals.**
- **The test set is a very safe place to work in.**
- **<u>Those who are interested in testing of their equipment are invited to use the APS PD test set.</u>**

The End