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# Cables and Terminations for Pulsed Power

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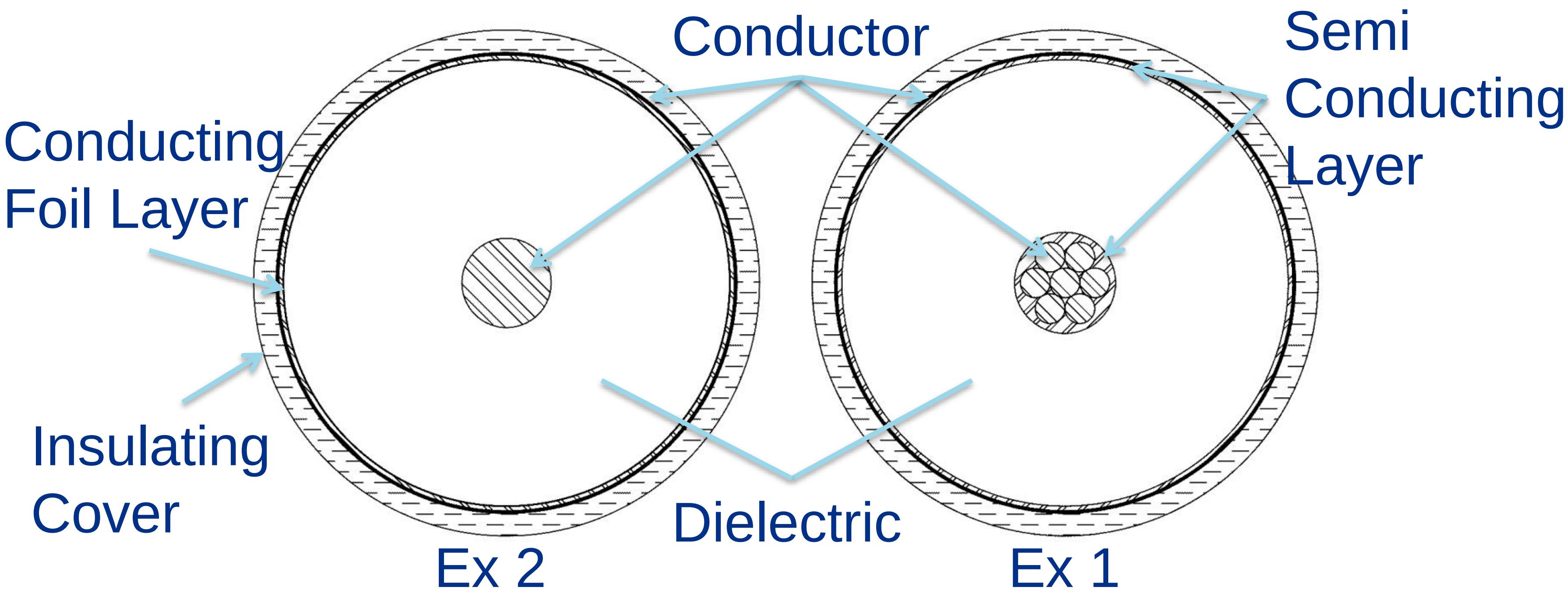
# Outline

- Coaxial cable and wire construction
  - Controlled impedance, controlled gradient
  - Pulse distortion
  - Pulsed vs DC
- Partial Discharge
- Terminations
- Examples
  - Kicker pulser
  - High voltage pulsed electrostatic quad

## Coaxial Cable construction




Two examples of coaxial cable construction

1) semi-conductive coated conductors to provide field grading for irregular surfaces

2) low loss cable with shield layer bonded to outside of dielectric to exclude air and very smooth center conductor

# Coaxial Cable construction

- Well defined impedance
  - $Z0=Sqrt[\mu/\varepsilon]/2\pi * Ln[r_o/r_i]$ for coaxial
- Defined impedance also controls electric field stress
  - $Emax = V/(r_i Ln[r_o/r_i])$ at center conductor for coaxial cable
    - At outer conductor may still be high $E = V/(r_o Ln[r_o/r_i])$
  - Assumes surface of conductors is perfectly smooth
- Characteristic "time constant" for lossy cables [1],[2],[3]
  - Skin effect and dielectric losses limit rise time at end of cable
  - Cables with semi conductive coating have additional losses
  - $V_{out} = Erfc[1/Sqrt[t/t_o]]$ for a rectangular pulse, only skin effect

    $t_0 = (A\,l)^2$ where l is length of cable and

    $A = Sqrt[\varepsilon/(2\sigma_c)]\,(1/r_i+1/r_o)/(2\,Ln[r_o/r_i])$ is a loss factor



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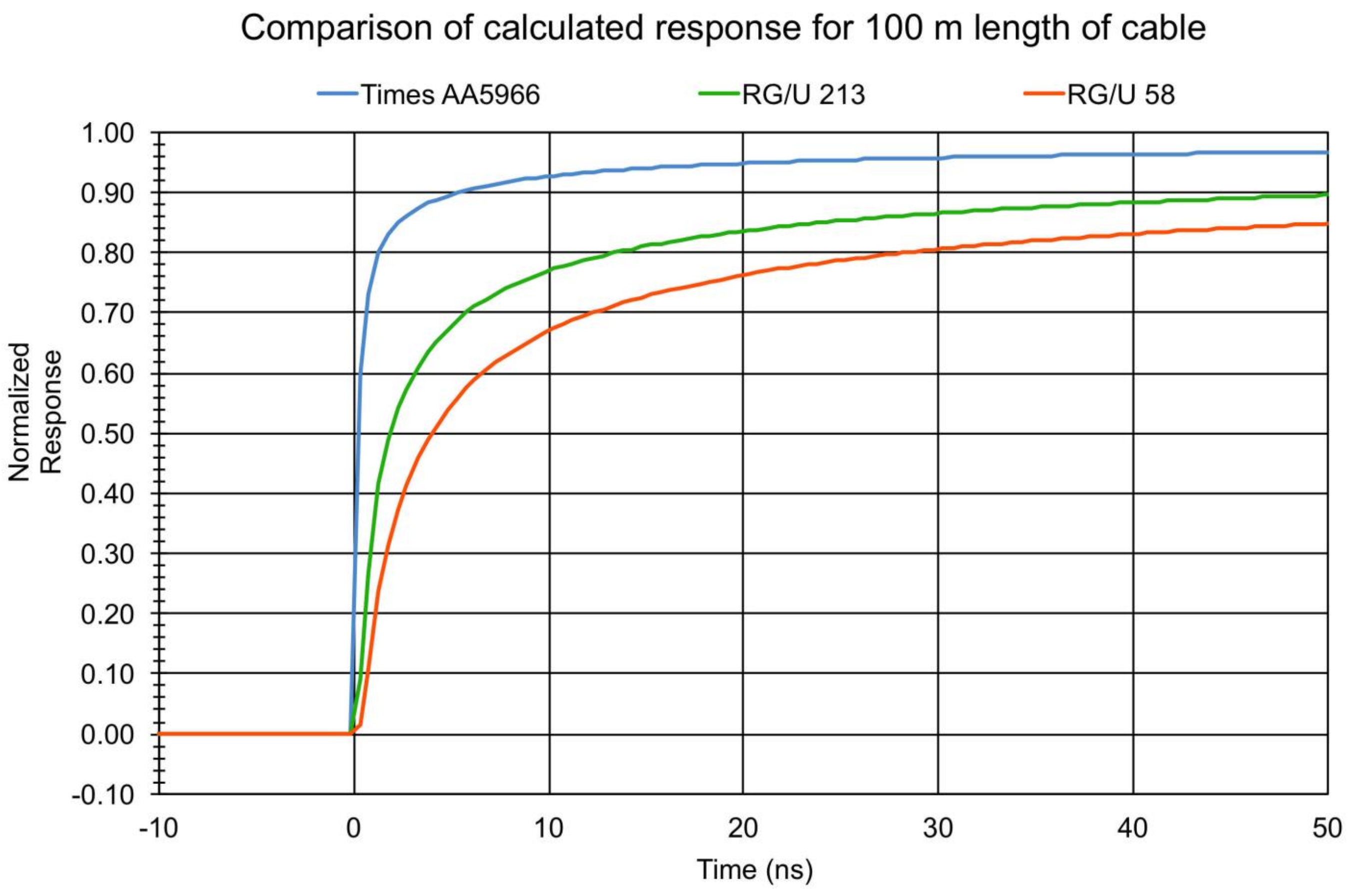
# Coaxial Cable Construction




Plot of Erfc [1/Sqrt[t/$t_o$] ] for several values to $t_0$

Values for Sqrt[$t_0$] with 100 meters of cable: RG/U 58 ~ 30 $10^{-6}$ Sqrt(sec) , RG/U 213 ~ 21 $10^{-6}$ Sqrt(sec), RG/U 220 ~ 11.9 $10^{-6}$ Sqrt(sec), Times 5966 best fit 12.3 $10^{-6}$ Sqrt(sec)

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# Coaxial Cable construction

- Why do cables or terminations fail?
  - Electric field causes ionization of a dielectric
- Discharge in air is usually the problem for long life designs
  - Air has a lower breakdown than solids or liquids
  - Creates ozone which is chemically active and attacks insulation
    - Even if choose a good cable a concern at termination
- Two solutions
  - Remove air space completely, smooth surfaces
    - Good cable construction
      - Difficult to do on parts that need to come apart
  - Make air space bigger so it can easily be filled with something
    - Seems counter-intuitive to some
      - Usually the issue at termination

## Wiring Description – An Aside

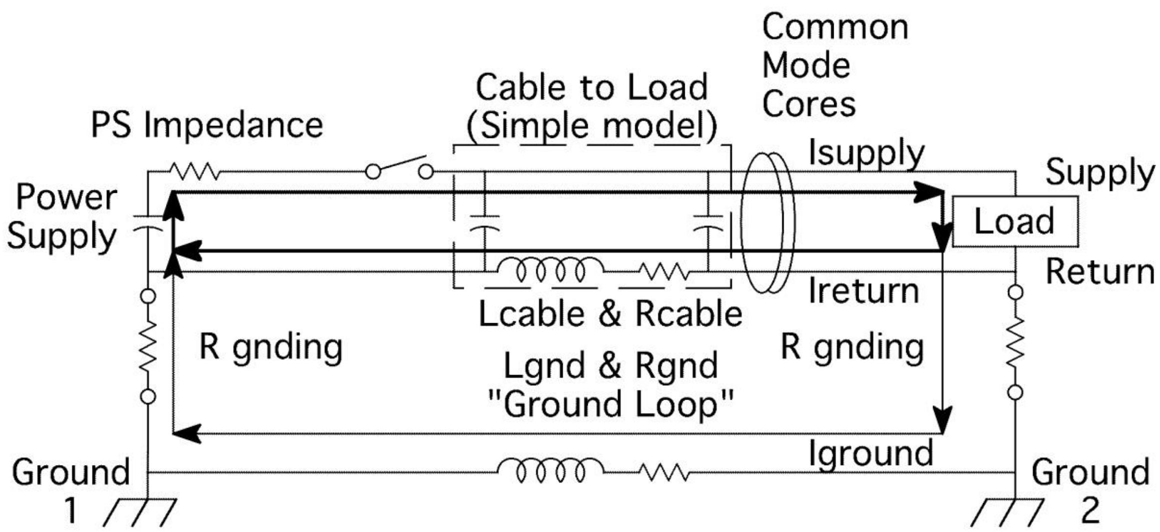
- When to use insulated wire for point to point connections?
- Inside cabinets and chassis if there is a space constraint?
  - The enclosure is providing safety and security
  - Maybe for DC wiring but still need to pay attention to routing
- Between cabinets?
  - Not if you need a shield around the wire for security or safety
- For a low impedance connection?
  - Could use a coax cable, but ends can be tricky
  - Change your layout so don't have long paths and run wire
- My personal suggestion is to almost never use insulated wire in a pulsed high voltage application
  - Use tubing and solder on large wire ring terminal
    - No insulation to fail, make smooth radius on wire terminals
    - For low rms current, can flatten tubing at end, remove sharp edges

# Cables and Grounding – An Aside

- Ground currents are the reality of multiple return paths
  - Many applications will require both the load and the power supply to be grounded locally for safety and security
  - The return path and the safety ground are connected at each location
- To have low ground current need to consider resistance, inductance and capacitance between return and ground

Use common mode impedance / cores around supply & return

Provides a higher impedance for currents flowing in ground loop



# Termination

- Commercial *vs.* Custom
  - Low voltage, ~ 5 kV, there are several standardized connections but attention to detail on assembly still required
    - HN, SHV, 10kV SHV
      - SHV and 10 kV SHV still DC rated parts, HN 50 Ohm, few $kV_{rms}$
      - Fermilab avoids MHV due to safety concerns
  - High voltage, there are very few standards, but still commercial
    - Lemo Y series, GES S150 series, Isolation Design, Dielectric Science, FID GmbH
  - Most high voltage connectors are rated for DC and low current
    - Probably not controlled impedance, but can still be used
  - Test short cable and connection for partial discharge with commercial equipment, 50 Hz / 60 Hz / 400 Hz
    - May not be sufficient to determine suitability, fast pulses distribute fields differently
    - A successful corona inception test for low frequency is practical starting point

# Termination

- Custom Terminations
  - Field boundary conditions from Maxwell
    - $D_{n1}=D_{n2} + \sigma_s$ (surface charge from free carriers is usually 0)
    - $E_{t1}=E_{t2}$
    - Differing dielectric constants cause bending of E field at boundaries, increase peak electric field stress
  - Conservative electric field stress levels in dielectrics
    - Operate at less than 50% of uniform field breakdown strength
      - less than 25% for very long life (> $10^9$ pulses)
    - Breakdown of air in uniform field at ~ 3 MV / m so design for maximum field of < 1.5 MV / m
  - Calculate maximum stress level in final geometry
    - Start of failure is at location of maximum, then just gets worse
  - Use simple geometries, uniform materials
    - Dielectric boundaries should be similar to equipotential surface

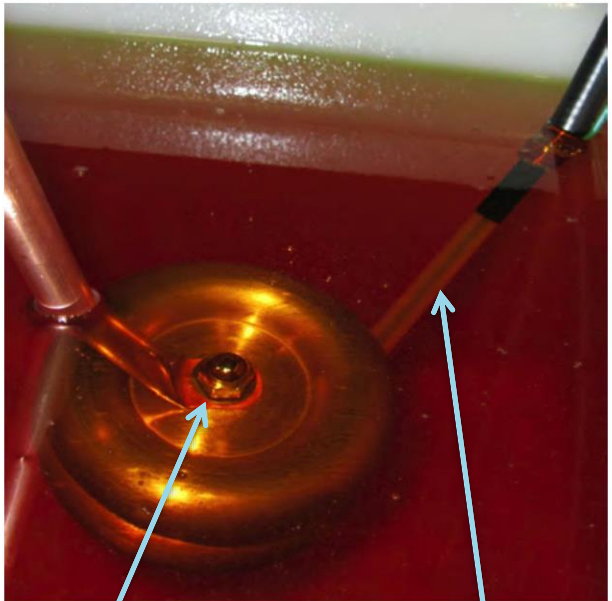
# Termination

- High current *vs.* Low Current
  - Bolting, soldering, welding most reliable
    - Difficult to do in most high voltage applications
  - Contact bands from Multi-Contact / Stäubli Electrical are designed for high current
    - High precision fitting parts for high pulse current
    - Use for inaccessible high voltage connections
  - Avoid EMI rated contact fingers and springs for high current
    - Contact pressure too low
      - Problems with uniform pressure along surface, poor current sharing
    - Short lifetime in high current pulsed applications
  - Contact material for many of these is BeCu alloy
    - May be safety issue in some locations

# Example 1: Commercial Cable and Commercial Connector

- Requirement, g-2 “electrostatic” quads
  - Pulse to 32 kV with several μs rise time, stable to < 0.5% for 700 μs, repeat with an average repetition rate of 12 pps
- Tested several cable types for partial discharge
  - Both ends placed under oil to prevent cables ends from being dominant
- Tested mated connector with other end under oil
  - Connector will be in air for final configuration
  - Needed to add dielectric grease (silicone) inside cable termination and between mating connectors
- Full description in note E989-doc-4307, V. Tishchenko
  - g-2 @ FNAL experiment note

# Example 1: Commercial Cable and Commercial Connector



Connection to corona test equipment

Cable under test

Terminated cable test

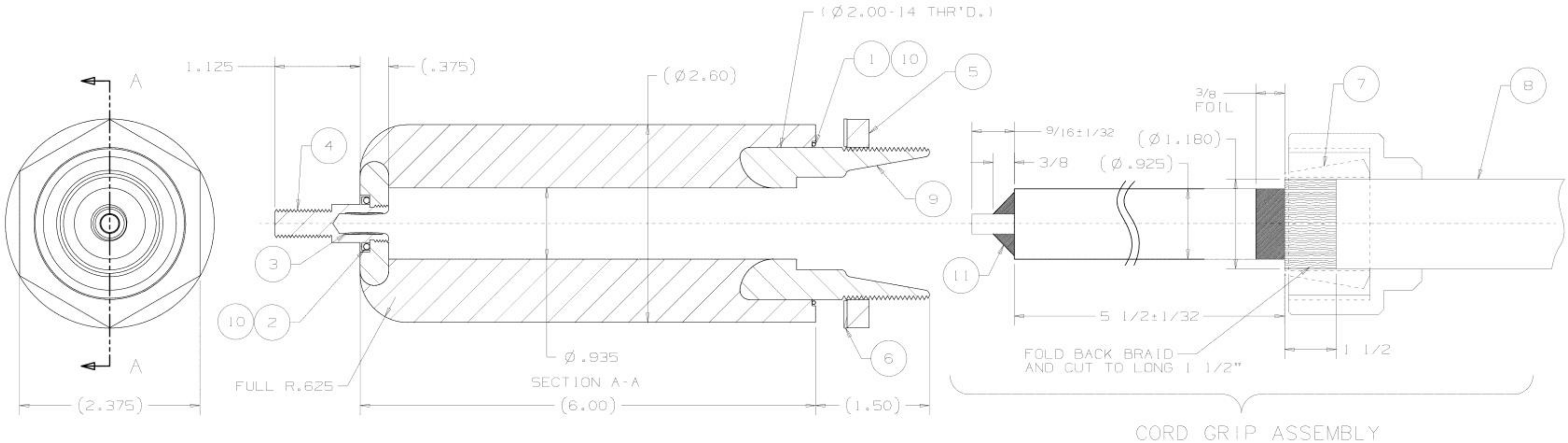
# Example 1: Commercial Cable and Commercial Connector

- Requirement is ~ 2 years for any failures at 12 pps, 32 kV peak, 700 µs pulse length, 12 installations
- Test results with Dielectric Science DS2124, cable only
  - in air 4.3 $kV_{rms}$ inception, in oil 12 $kV_{rms}$ inception
    - This cable has grading material around center only, 100 kVDC
- Test results with Dielectric Science DS2124B, cable only
  - in air, 4.3 $kV_{rms}$ inception, in oil >30 $kV_{rms}$ inception
    - This cable has grading material around center and shield
- Test results DS2124B and GES S150/B150 (50 kVDC, 30 A)
  - one end DS2124B in oil, other in connector 7.8 $kV_{rms}$ inception
  - one end DS2124B in oil, greased up connector, 16 $kV_{rms}$ incept

# Example 2: Semi Custom Cable and Connector

- Have been using special version of RG220 from Times Microwave for 20 years ( AA-5966 )
  - Cable has two layers of foil bonded to outside of polyethylene core covered with copper braid – no air space
  - All cable is acceptance tested by Fermilab with charge to 60 kV and discharge into matched load for 500,000 pulses
- Have been using connectors made by Isolation Products for 20 years (D-1023 and D-1024)
  - Early design had a failure point on outside for contact band
    - Fixed with a threaded connection, Multilam band inside connector
  - Use of dielectric grease and proper trimming of outer foil
  - Update for lower inductance design (D-1023F)

# Example 2: Semi Custom Cable and Connector

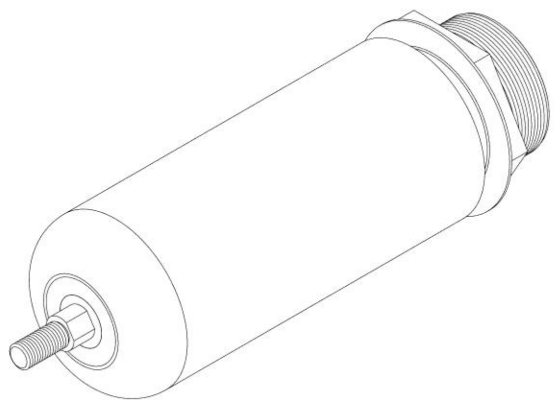



ISOLATION PRODUCTS
157 SAN LAZARO
SUNNYVALE, CA. 94086

PH. #(408)-730-4672

NOTES:

1. NEED TO ORDER "D-1024 WITH MB-337782 TIP" THERE ARE SEVERAL DIFFERENT STYLES OF TIPS. ITEMS 5,6,7,9 ARE INCLUDED IN PART # D-1024.
2. ITEMS #4,#5,#6 NEED TO BE BRIGHT ACID TIN PLATED 0.0003 - 0.0007" THICK BEFORE USE. VENDOR DOES NOT PLATE.



| ITEM | VENDOR | PART NO | PART NAME | QTY |
|---|---|---|---|---|
| 11 | DOW CORNING #4 | N/A | ELECTRICAL INSULATING COMPOUND | A/R |
| 10 | APEZION L | N/A | HIGH VACUUM GREASE | A/R |
| 9 | | F10043994 | D-1024 CAST EPOXY BODY W/ MOUNTING HUB & END CAP | 1 |
| 8 | ES-159896 | N/A | TIMES CABLE AA-5966 | |
| 7 | | N/A | RUBBER WASHER | |
| 6 | | F09017260 | FLAT WASHER 2.75 OD BRASS | 1 |
| 5 | | F09016582 | HUB NUT BRASS 2.000-14UNS | 1 |
| 4 | | F00337782 | THREADED STUD D 1023 F CONN | 1 |
| 3 | TYCHO/AMP 4-192038-8 | F09095818 | BAND | 1 |
| 2 | PARKER 2-112 | N/A | O-RING .487 ID X .103 NOM | |
| 1 | PARKER 2-226 | N/A | O-RING 1.984 ID X .139 NOM | |

UNLESS OTHERWISE SPECIFIED

| ±.X | ±.XX | ±.XXX | ±X/X | ±X° |
|---|---|---|---|---|
| .1 | .02 | .005 | 1/16 | 1° |

BREAK ALL SHARP EDGES .015 MAX.
DO NOT SCALE DRAWING
DIMENSIONS BASED ON ASME Y14.5-2009
MAX. ALL MACH SURFACES 125
DRAWING UNITS: INCHES

| | | | |
|---|---|---|---|
| DRAWN | H.PHAM | DATE | 03-Jun-2015 |
| CHECKED | C.JENSEN | DATE | 31-Aug-2015 |
| APPROVED | C.JENSEN | DATE | 31-Aug-2015 |

USED ON F10043160

MATERIAL

FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY

NAME: D-1024 CAST EPOXY BODY ASSEMBLY

| SCALE | SIZE | DRAWING NUMBER | SHEET | REV |
|---|---|---|---|---|
| 1:1 | C | F10042071 | 1 OF 1 | - |

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# References


- [1] R.L. Wigington, N.S. Nahman, Transient Analysis of Coaxial Cables Considering Skin Effect, Proceedings of the IRE, Feb 1957, pp 166-174
- [2] Q. Kern, F. Kirsten, C. Winningstad, Pulse Response of Coaxial Cables, Lawrence Radiation Lab, UC Berkeley, Counting Note CC 2-1b, July 1966
- [3] H. Riege, High Frequency and Pulse Response of Coaxial Transmission Cables with Conductor, Dielectric and Semiconductor Losses, CERN Note 70-4, PS Department, Feb 1970