# Everything you need to know to choose the right cable assembly

# RADIO FREQUENCY

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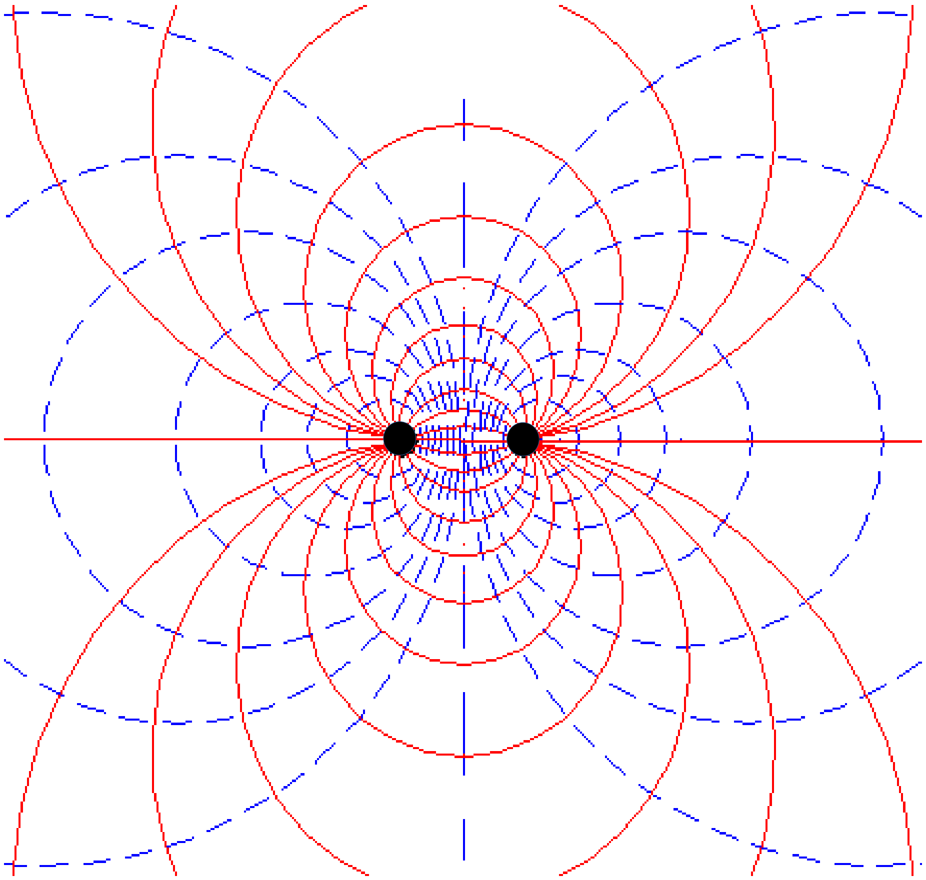
Materials and Engineering Technologies for Particle Accelerator Beam Diagnostig Instruments

# Attenuation

To connect a signal from A to B two wire will work.



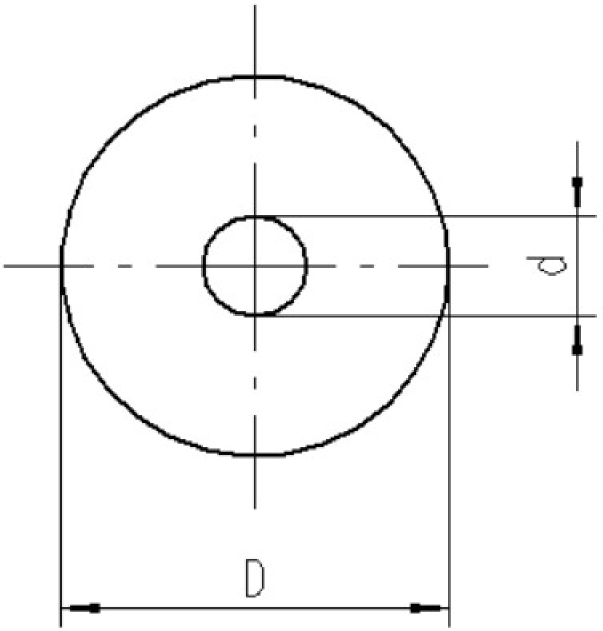
# Coaxial Cable

$$Z_L = \frac{Z_0}{2 \cdot \pi \cdot \sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \qquad (1)$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \qquad (2)$$

$$\epsilon_0 = \frac{1}{\mu_o \cdot c^2} \qquad (3)$$

$$Z_L = \frac{\mu_0 \cdot c}{2 \cdot \pi} \cdot \frac{1}{\sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \qquad (4)$$



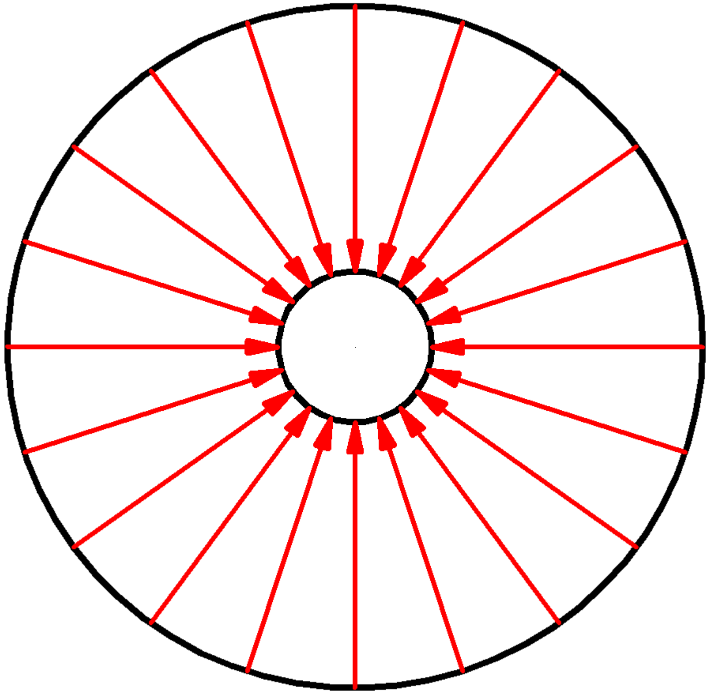

Approximate Equation

$$Z_L \approx \frac{60\Omega}{\sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \qquad (5)$$

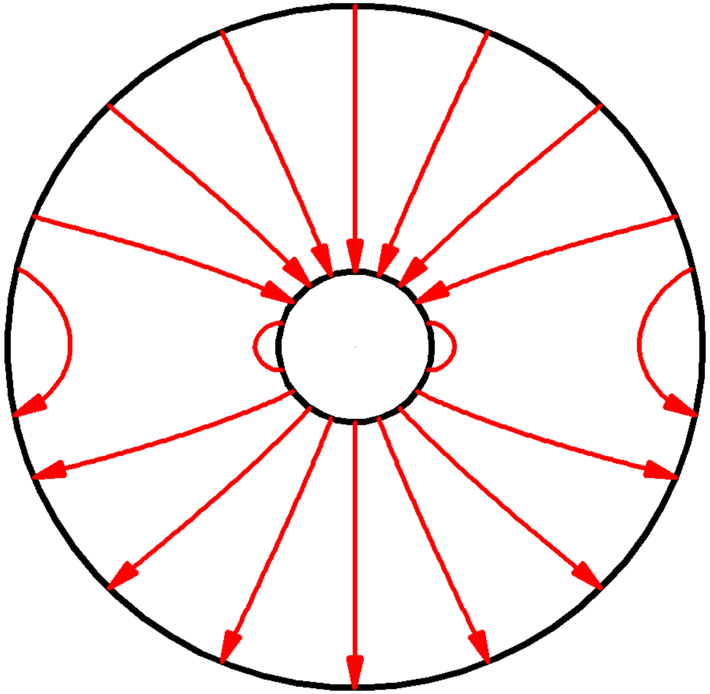
| | | |
|---|---|---|
| $\mathrm{Z_L}$ | : | Impedance |
| $\mu_0$ | : | Vacuum permeability $4 \cdot \pi \cdot 10^{-7} \frac{N}{A^2}$ |
| $c_0$ | : | Speed of light 299 792 458 $\frac{m}{s}$ |
| $\epsilon_r$ | : | Permittivity of dielectric |
| D | : | Shild diameter |
| d | : | Inner Conductor diameter |

# Coax Mode

The coax-cable can be use for DC signal
Does it has a maximum frequency?



TEM-Mode



TE11-Mode

# Coax Mode

The coax-cable can be use for DC signal
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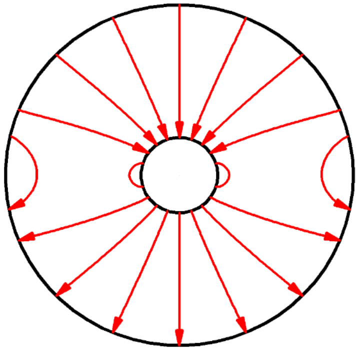
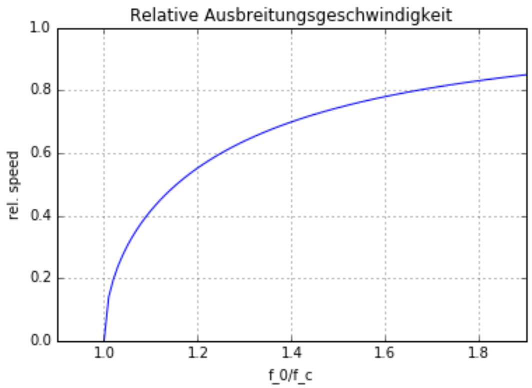





$$\Big(J_0(x\cdot A)-J_2(x\cdot A)\Big)\cdot\Big(Y_0(x)-Y_2(x)\Big)-\Big(Y_0(x\cdot A)-Y_2(x\cdot A)\Big)\cdot\Big(J_0(x)-J_2(x)\Big)=0 \quad (6)$$

$$A=\frac{R}{r} \quad (7)$$

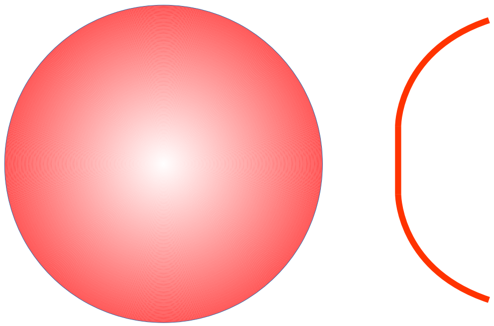
$$f_c=\frac{x\cdot c_0\cdot(A+1)}{(R+r)\cdot 2\cdot\pi\cdot\sqrt{\epsilon_r}} \quad (8)$$

$J_n$ : Bessel function first kind
$Y_n$ : Bessel function second kind
R : Shield radius
r : Inner conductor radius

# Skin Depth

With increasing the frequency the current is distributed in the wire such that the current density is largest near the surface.

To keep the equation simple we consider $\mu_r = 1$.



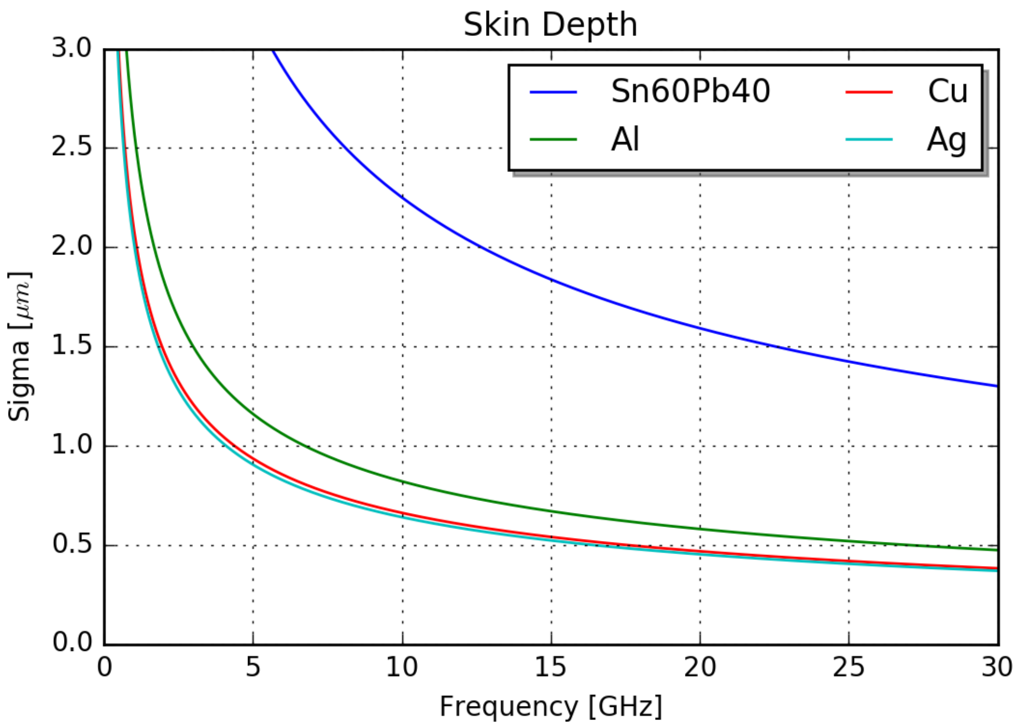
Skin Depth $$\varsigma = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \mu_r \cdot \sigma}}$$

Example

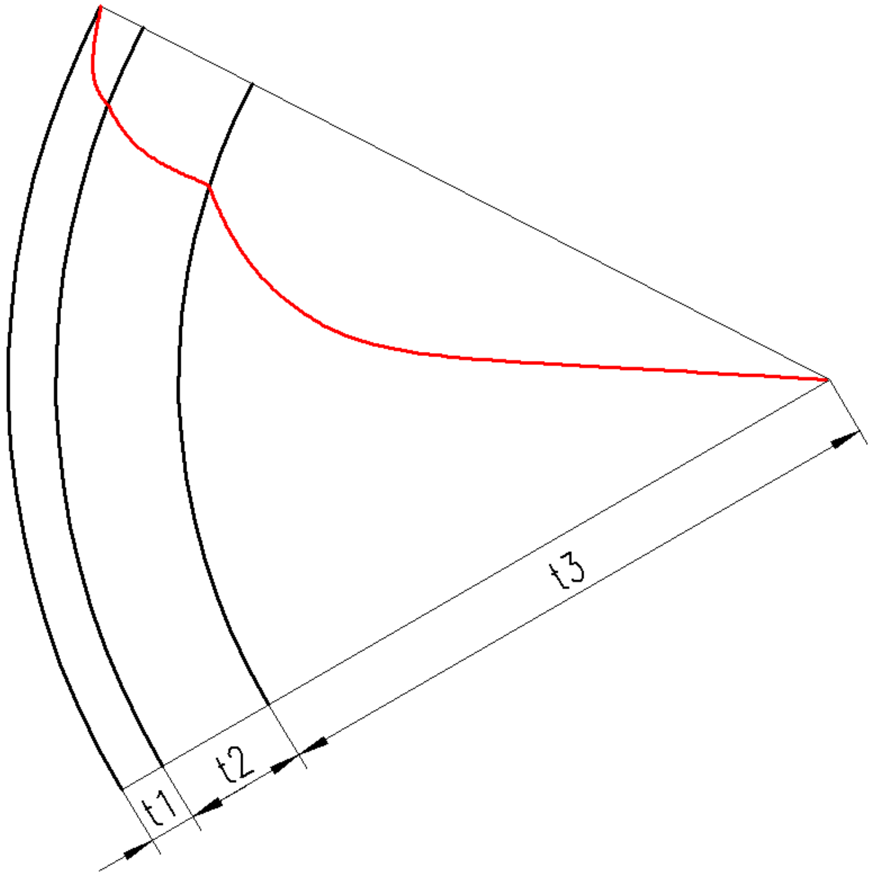
A 1mm diameter Copper wire at F = 1 MHz
Skin Depth = 65 µm

⇒ At a distance of 0.325 mm from the surface isn't any current!

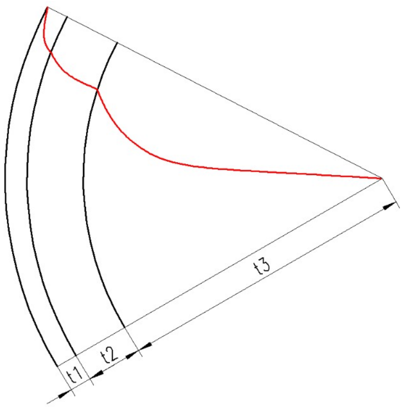
# Skin Effect



Skin Depth
Sn60Pb40
Cu
Al
Ag
Sigma [$\mu m$]
Frequency [GHz]
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
25
30

t1
t2
t3

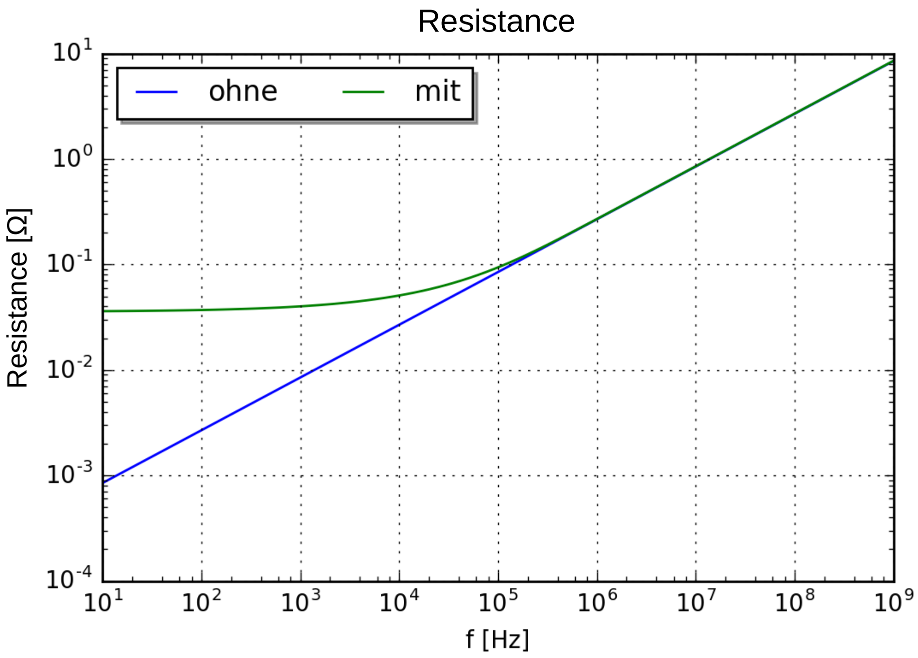



$$\zeta(i) = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \sigma(i)}} \tag{19}$$

$$B(1) = 0 \quad B(i+1) = \frac{t(i)}{\zeta(i)} \tag{20}$$

$$G_{tot} = 2 \cdot \pi \cdot \sum_{i=1}^{n} \zeta(i) \cdot \sigma(i) \cdot \left(e^{-B(i)} - e^{-B(i+1)}\right) \tag{21}$$

$$a_R = \frac{20}{ln(10)} \cdot \frac{1}{G_{tot} \cdot 2 \cdot Z_L} \quad \left[\frac{dB}{m}\right] \tag{22}$$





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# Resistive Loss

$$R_S = \sqrt{\frac{\pi \cdot f \cdot \mu_0 \cdot \mu_r}{\sigma}} \tag{11}$$

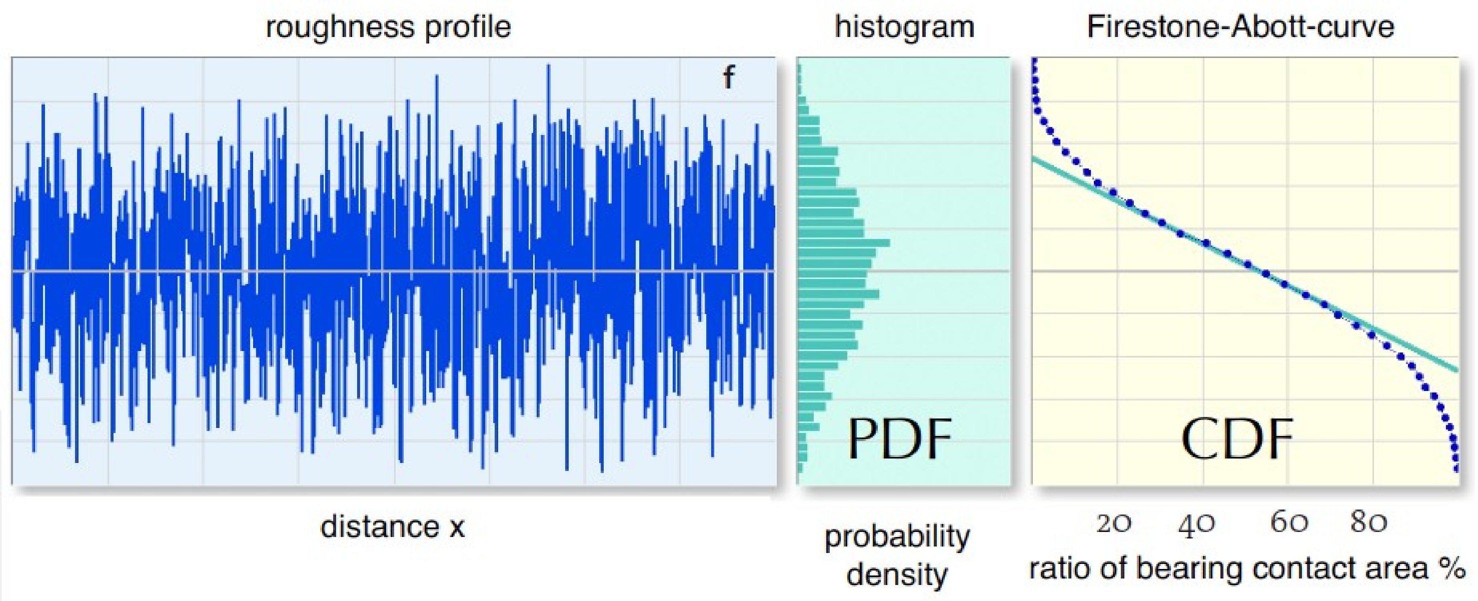
$$R_i = \frac{R_{Si}}{\pi \cdot d} \tag{12}$$

$$R_o = \frac{R_{So}}{\pi \cdot D} \tag{13}$$

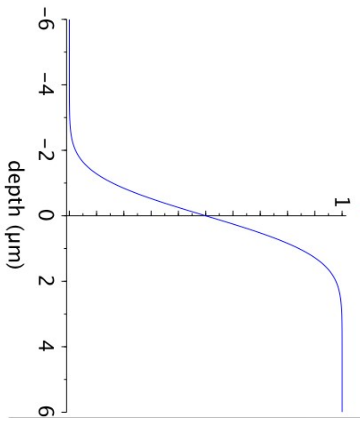
$$\alpha = \frac{R}{2 \cdot Z_L} \left[\frac{Np}{m}\right] \tag{14}$$

$$\alpha = \frac{20}{ln(10)} \cdot \frac{\sqrt{\pi \cdot f \cdot \epsilon_0 \cdot \epsilon_r}}{ln(\frac{D}{d})} \cdot \left(\frac{1}{d \cdot \sqrt{\sigma_i}} + \frac{1}{D \cdot \sqrt{\sigma_o}}\right) \tag{15}$$

# Rough Surface




**normally distributed surface profile: one single model parameter: Rq !**





$$\sigma(x) = \sigma_{\mathrm{DC}} \cdot \mathrm{CDF}(x) = \sigma_{\mathrm{DC}} \cdot \int_{-\infty}^{x} \mathrm{PDF}\, du = \sigma_{\mathrm{DC}} \cdot \int_{-\infty}^{x} \exp\left(-\frac{u^2}{2R_q^2}\right)\, du$$

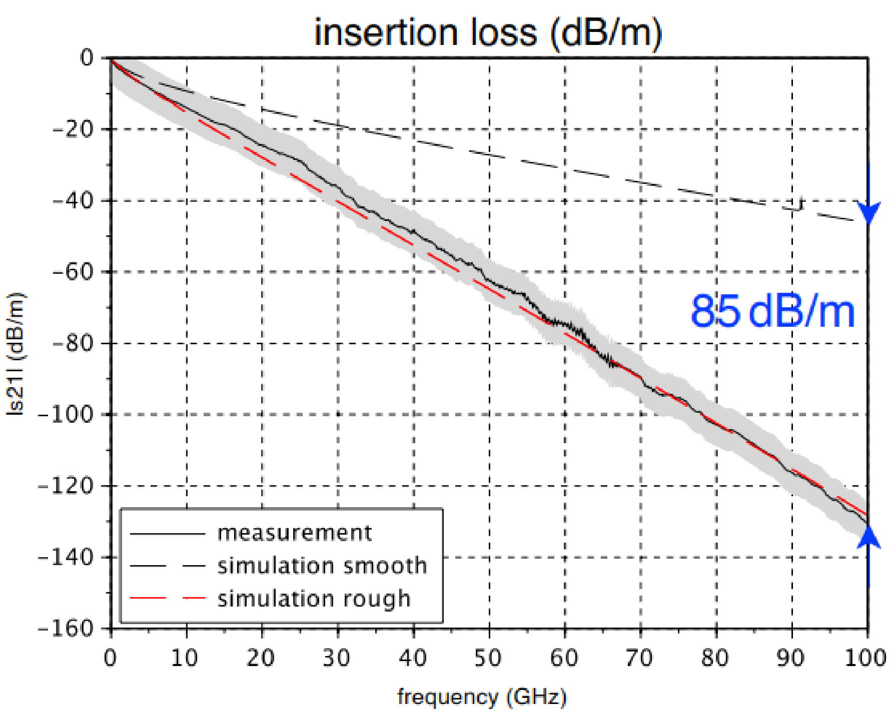
Dr.-Ing. G. Gold, Institute of Microwave and Photonics, FAU Erlangen-Nürnberg, EUC 2016

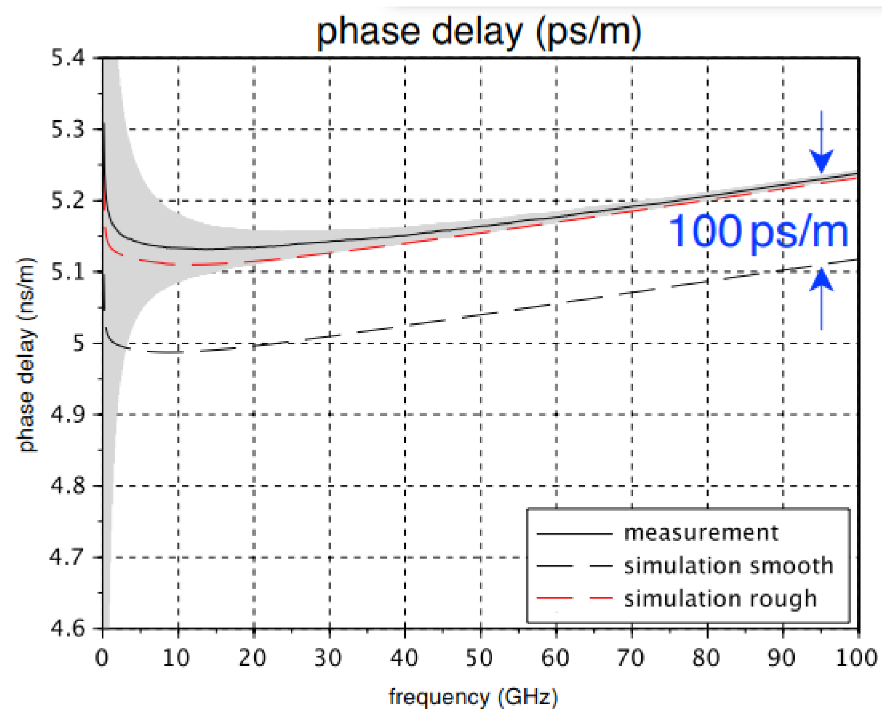
# Rough Surface

## Surface Impedance

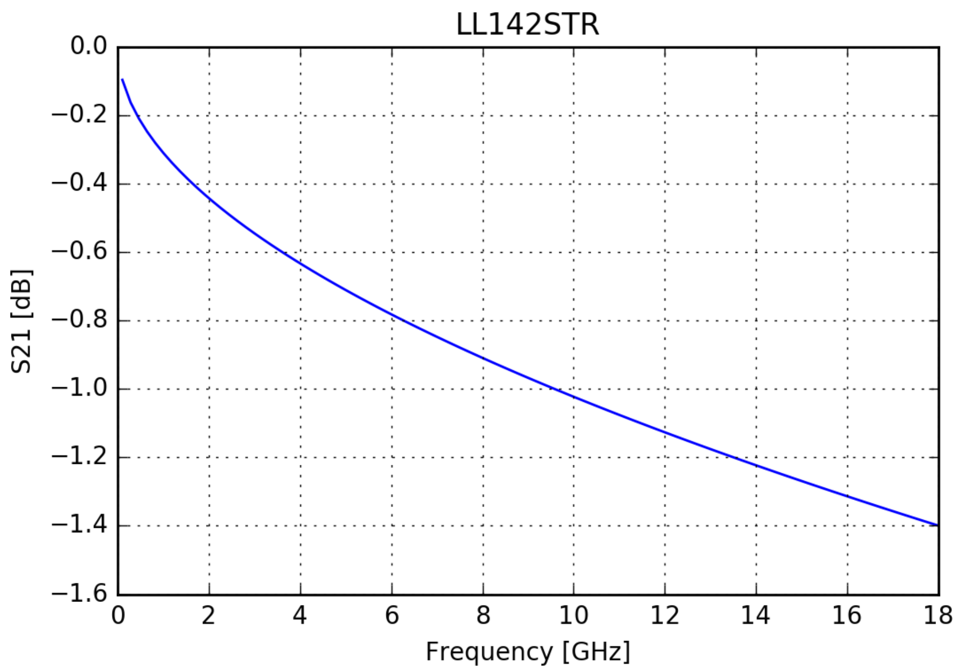
$$Z_\square = R_\square + j\omega L_\square = -\mu_0 \frac{E_z}{B_y} \quad \longrightarrow \quad Z_{\square,\mathrm{rough}} = -j\omega \frac{\int_{\sigma>0} B_y \, dx}{\int_{\sigma>0} J_z \, dx}$$

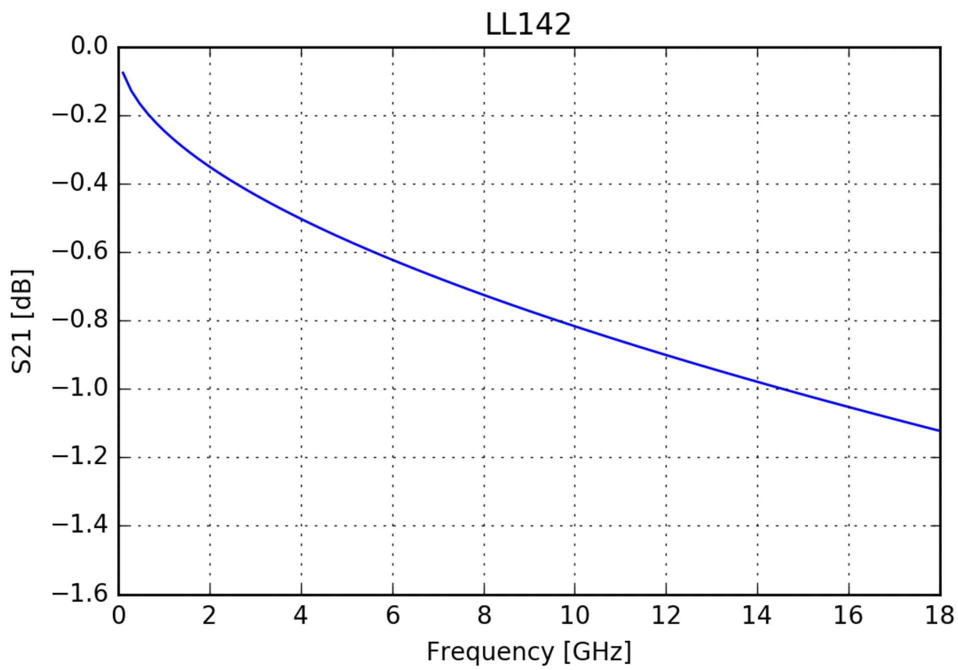
Example of a Microstrip Line



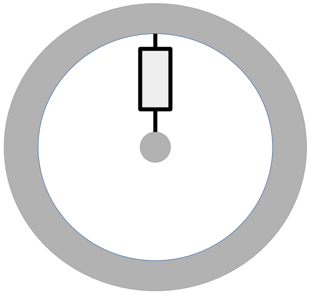



# Rough Surface



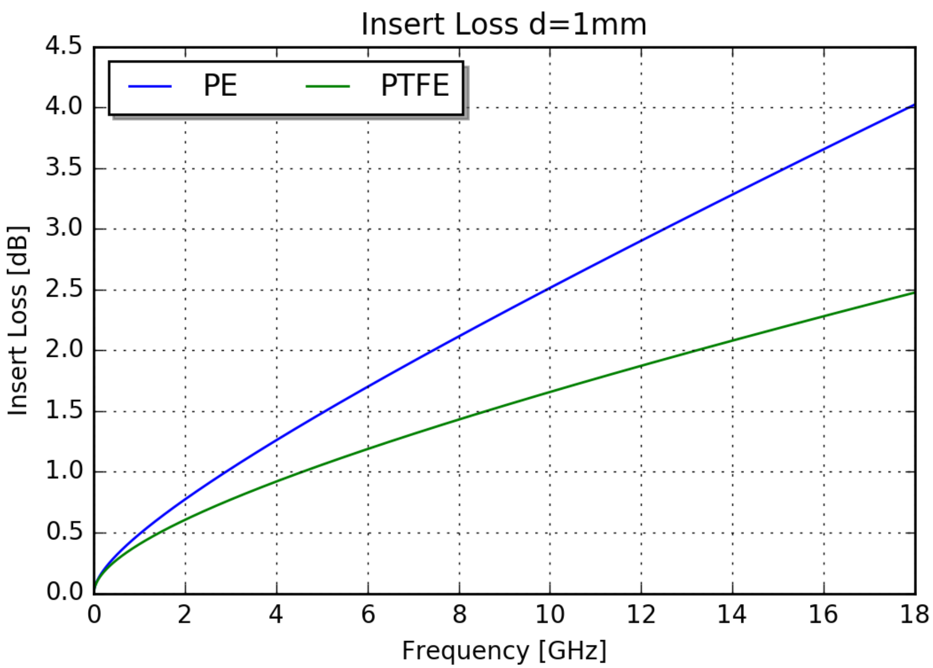



# Dielectric Loss



$$\alpha_D = \frac{20}{ln(10)} \cdot \frac{\pi \cdot f \cdot \tan(\delta) \cdot \sqrt{\epsilon_r \cdot \mu_r}}{c_0} \tag{16}$$

Typical insulator are Polyethylene (PE) and Polytetrafluoroethylene (PTFE)



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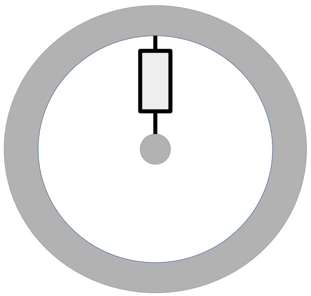

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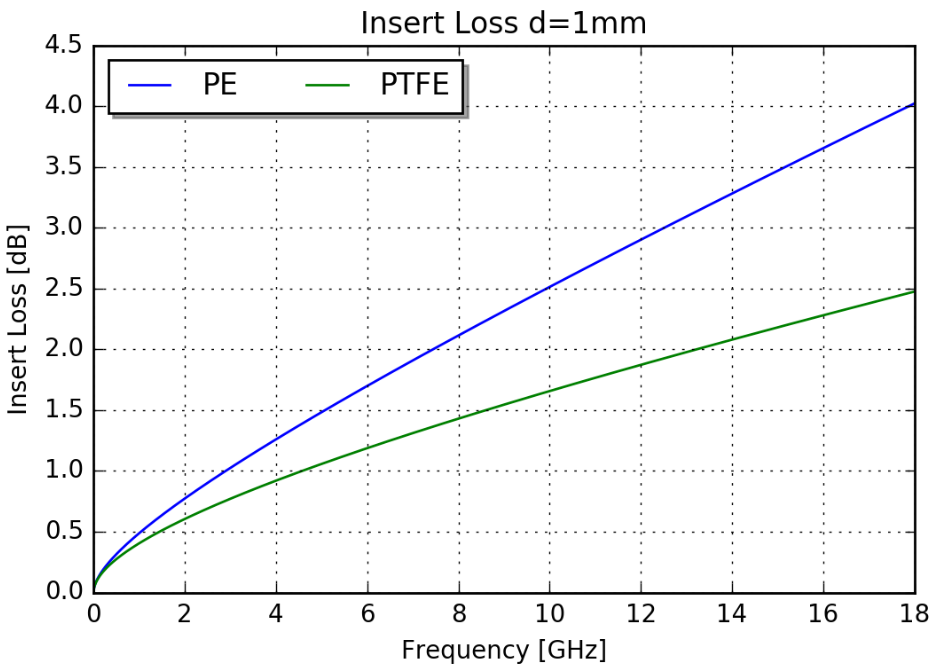
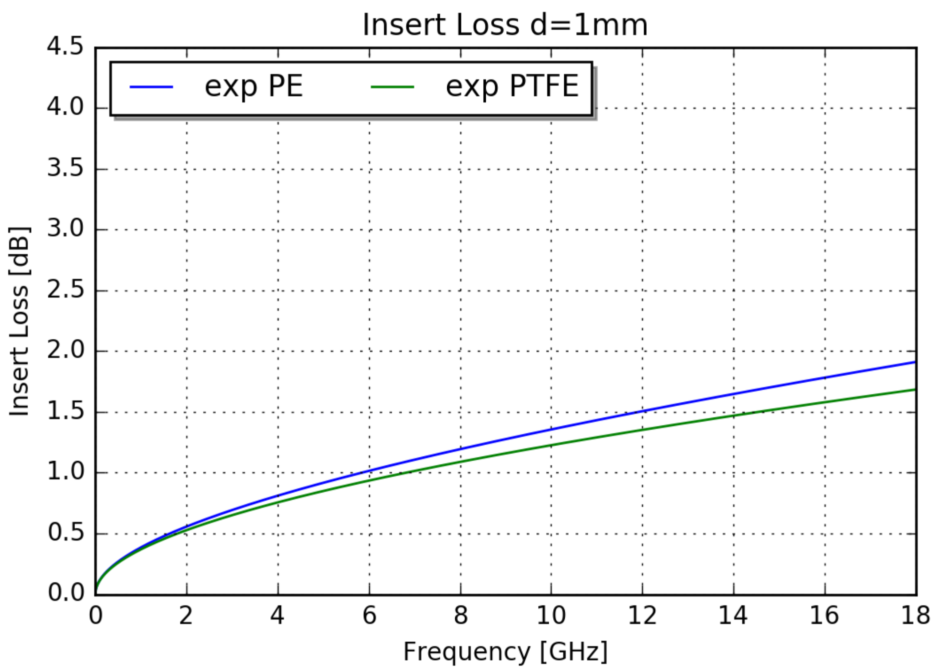


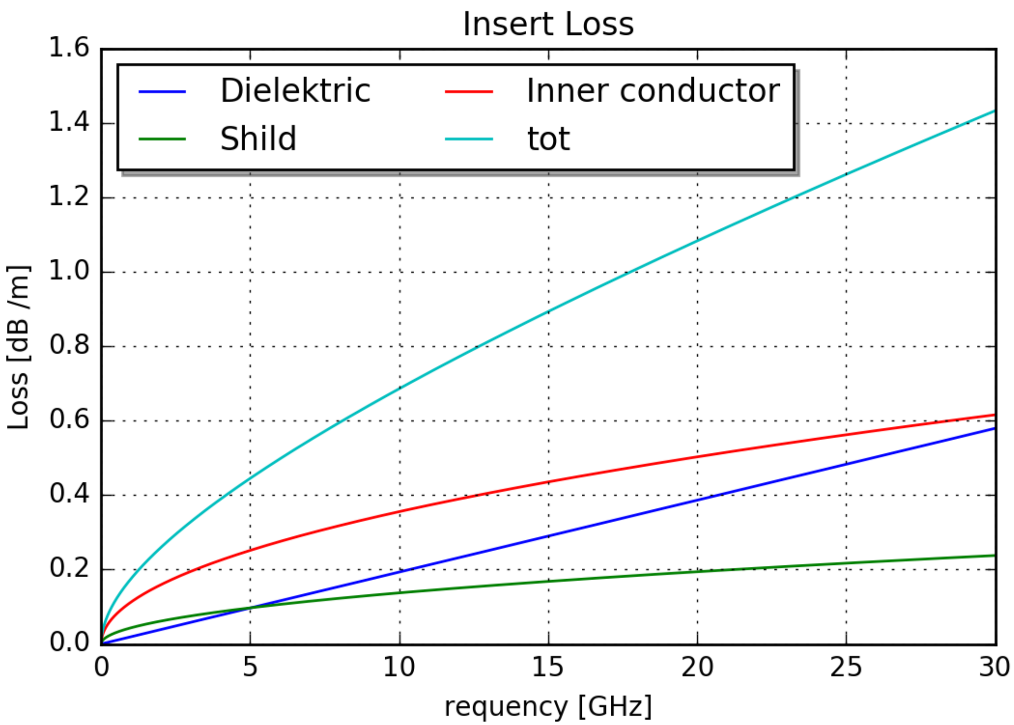



# Coax-Cable Loss

$$\alpha = \frac{20}{ln(10)} \cdot \frac{\sqrt{\pi \cdot f \cdot \epsilon_0 \cdot \epsilon_r}}{ln(\frac{D}{d})} \cdot \left(\frac{1}{d \cdot \sqrt{\sigma_i}} + \frac{1}{D \cdot \sqrt{\sigma_o}}\right)$$

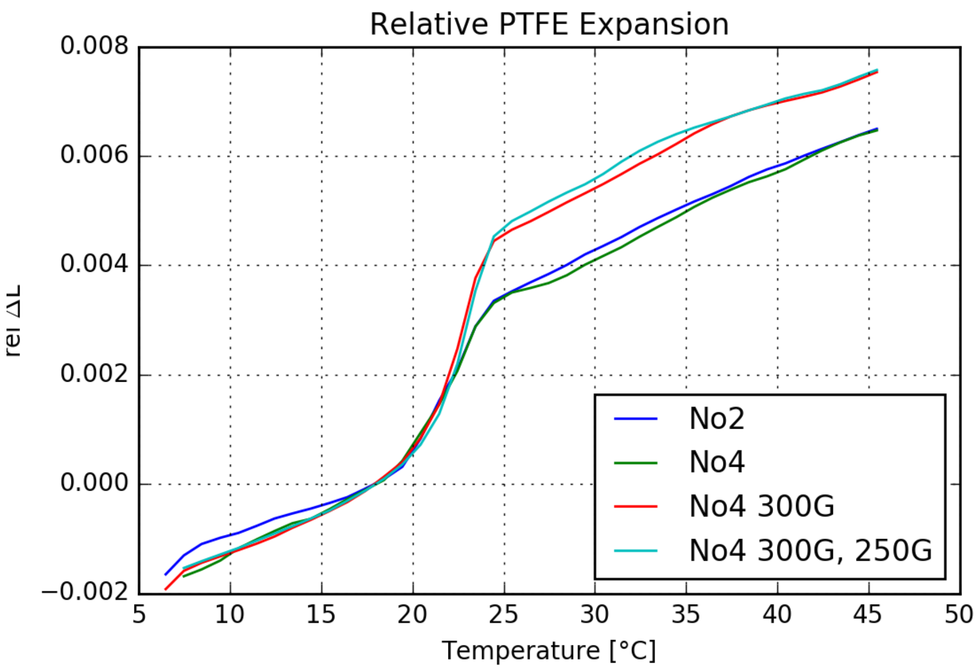
$$\alpha_D = \frac{20}{ln(10)} \cdot \frac{\pi \cdot f \cdot \tan(\delta) \cdot \sqrt{\epsilon_r \cdot \mu_r}}{c_0}$$

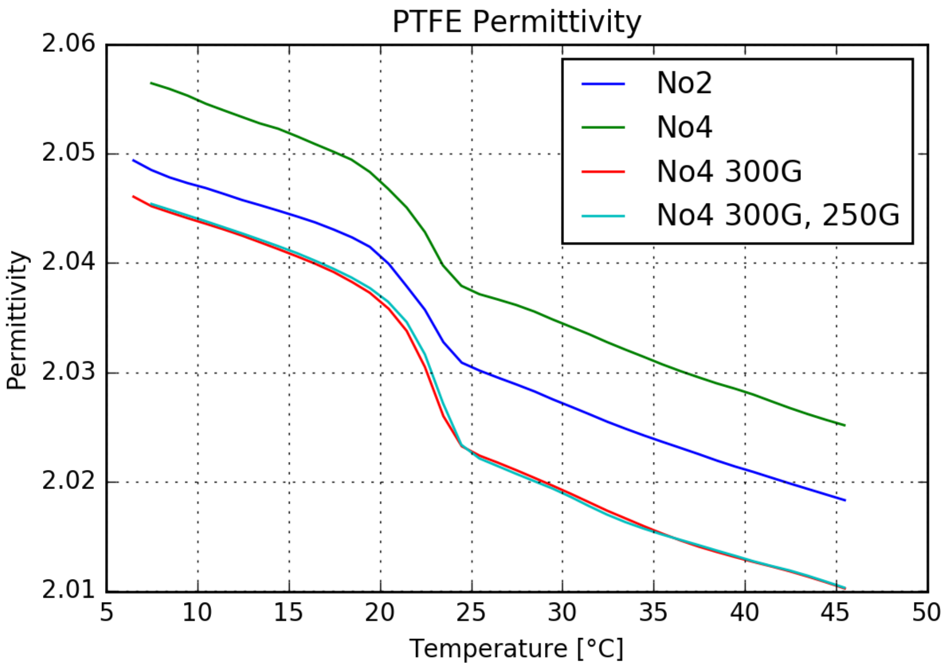
$$IL = l \cdot \left(K1 \cdot \sqrt{f} + K2 \cdot f\right)$$



# Velocity

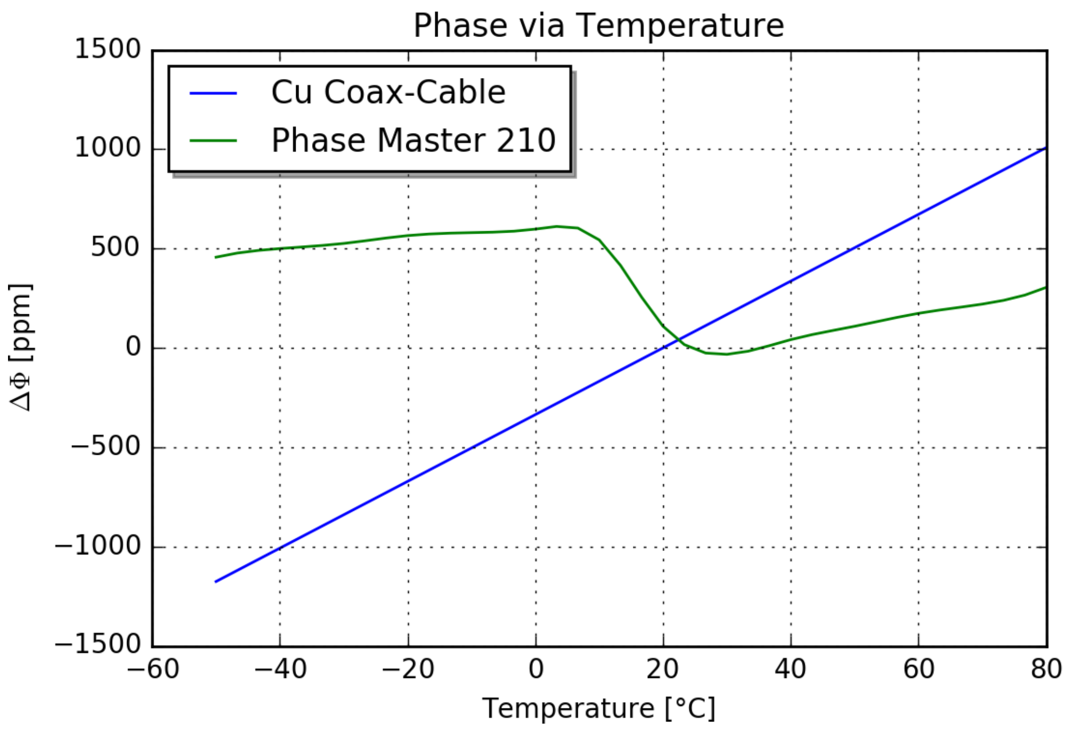
$$v = \frac{c_0}{\sqrt{\epsilon_r(T, f)}}$$



# Phase Stability via Temperature

Trough the material expansion when the temperature increase the coax-cable will be longer. This result in a phase change compare to room temperature.



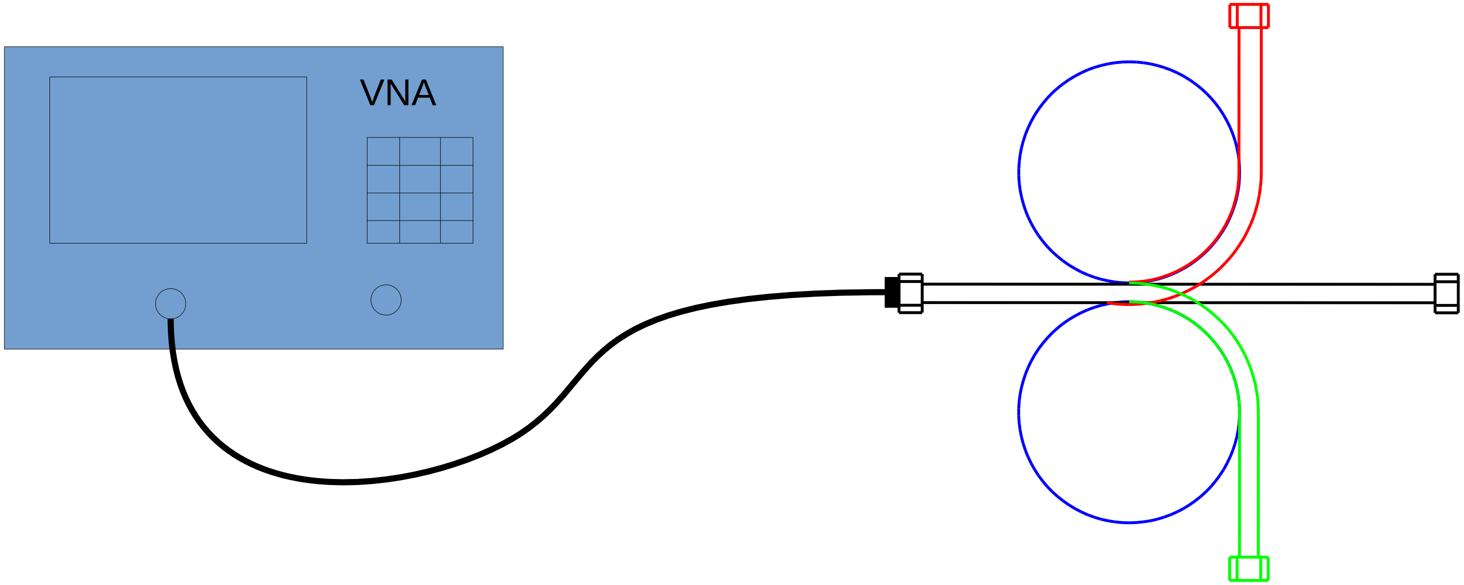

$$\Phi = \frac{l}{\lambda} \cdot \sqrt{\epsilon_r} \cdot 360^\circ \quad (17)$$

$$\Delta\Phi = \frac{\Delta\varphi}{\Phi} \cdot 10^6 [ppm] \quad (18)$$

# Phase Stability via Bending

If you bend a coax-cable the pressure on the dielectric increase and the diameter will deform This results in a phase change.

There is no standard test.
Different companies perform different test.



# Peak Power

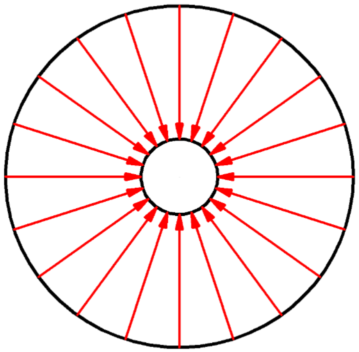
The restriction for peak power is the arcing which will damage the cable.

$$E_d = \frac{V_{peak}}{r \cdot \ln\left(\frac{R}{r}\right)}$$

$$V_{peak} = E_d \cdot r \cdot \ln\left(\frac{R}{r}\right)$$

$$P_{peak} = \frac{E_d^2 \cdot r^2 \cdot \ln\left(\frac{R}{r}\right) \cdot \sqrt{\varepsilon_r}}{120\,\Omega}$$

$E_d$ : Electric field
$V_{peak}$ : Peak voltage
R : Dielectric radii
r : Inner wire radii



Dielectric strength PTFE ≈ 100MV/m
Air ≈ 1MV/m

→ 50Ω coax-cable with r = 3mm

Air $P_{peak}$ = 64.2 kW
PTFE $P_{peak}$ = 1.35 GW → 13.5 MW

With margin



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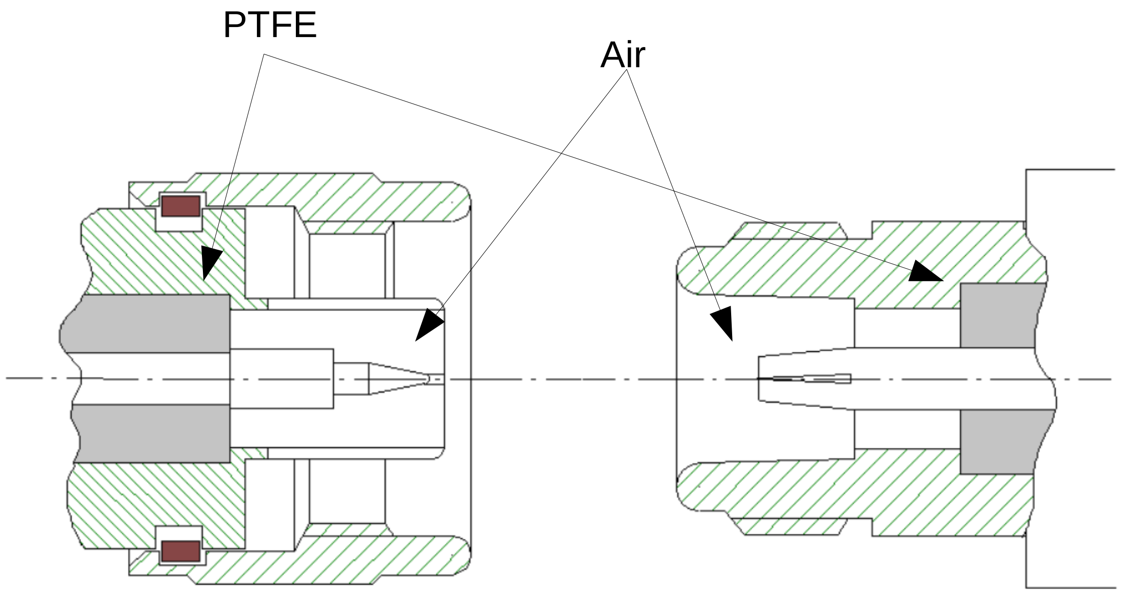
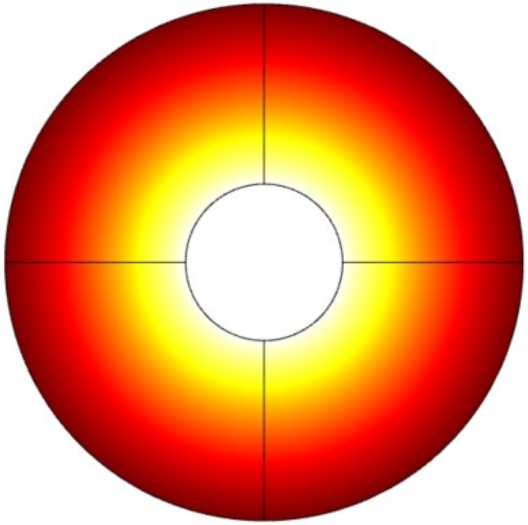
# Peak Power

Weakest part is in the connectors

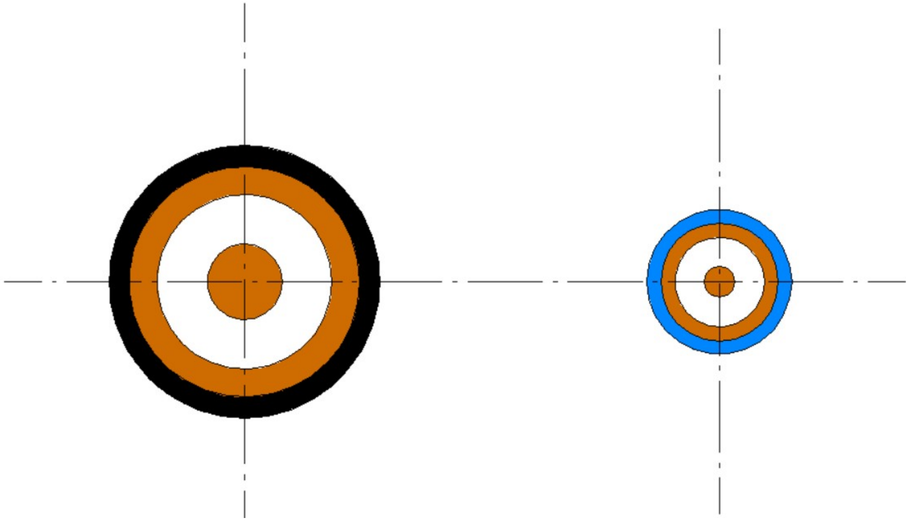



N-connector

# Average Power



- Highest loss at surface of inner contact
- Continues serving temperature of insulator
  - PTFE 250°C
  - PE 80°C
  - TF4™ 150°C



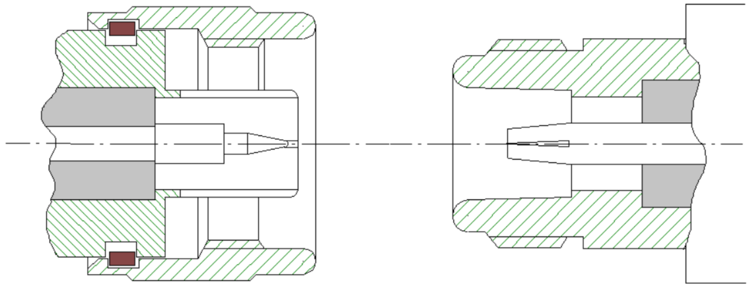
3/8” Flexwell ePE

640 W @ 1 GHz

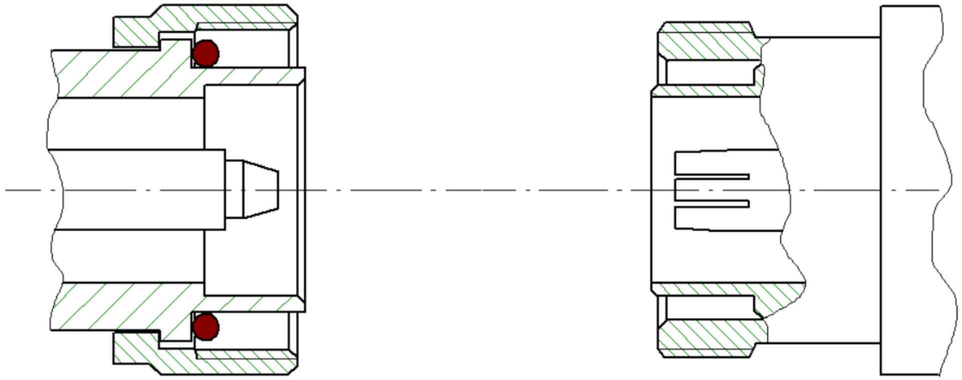
LL142 ePTFE

720 W @ 1 GHz

# Average Power



N-connector 1100W @ 1GHz
$f_{max}$ = 11 GHz



7/16-connector 2300W @ 1GHz
$f_{max}$ = 8.3 GHz

At sea level !

# Power via Pressure

Paschen's law

$$V_B = \frac{B}{\ln(A \cdot p \cdot d) - \ln(\ln(1+\gamma^{-1}))} \cdot p \cdot d$$

Air

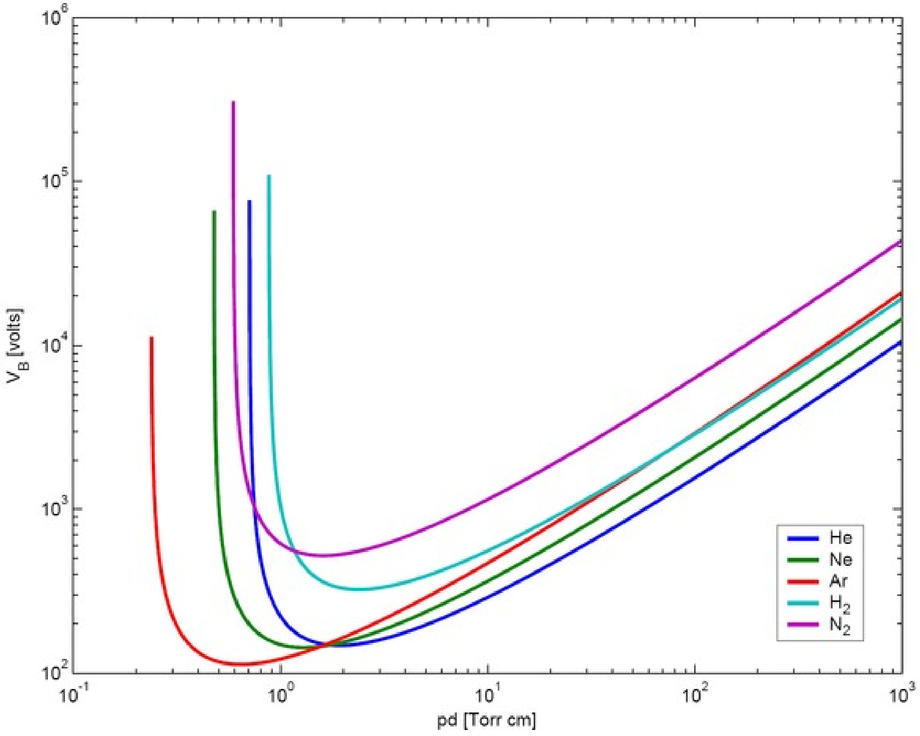
A = 10.95 (Pa * m)$^{-1}$ B = 273.8 V*(Pa * m)$^{-1}$

$V_B \approx 47$ V $\Rightarrow P_B \approx 44$ W

Helium

A = 2.25 (Pa * m)$^{-1}$ B = 25.5 V*(Pa * m)$^{-1}$

$V_B \approx 21$ V $\Rightarrow P_B \approx 8.8$ W



# Shielding

A single braid shield has an overlapping of 80% to 97%

→ Shielding effectiveness up to 40 dB @ 1GHz

Two braid shield

→ Shielding effectiveness up to 80 dB @ 6 GHz

# Shielding

Best shielding for flexible cable is with a foil and braid

→ Shielding effectiveness up to 110 dB @ 26.5GHz

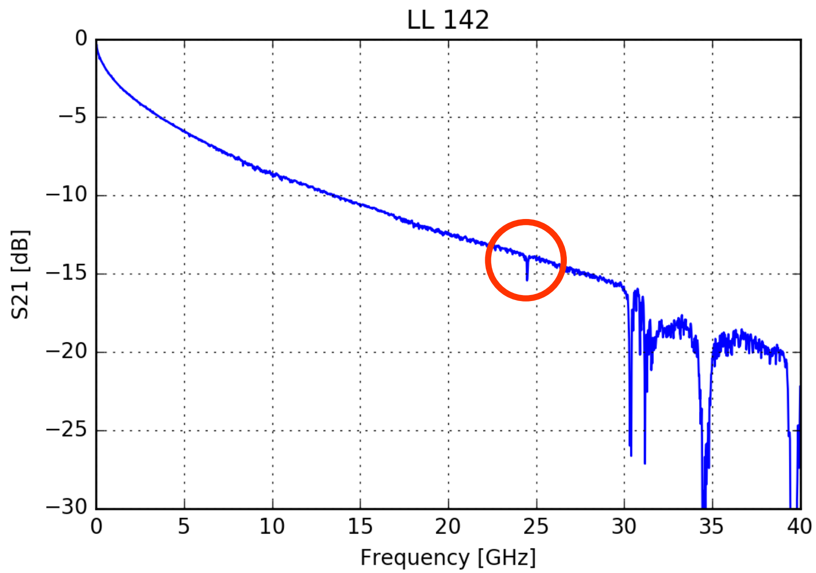
Best shield is a pipe!
Measurement of more than 120 dB is difficult and if you get an result it could be from leakage of the connectors.

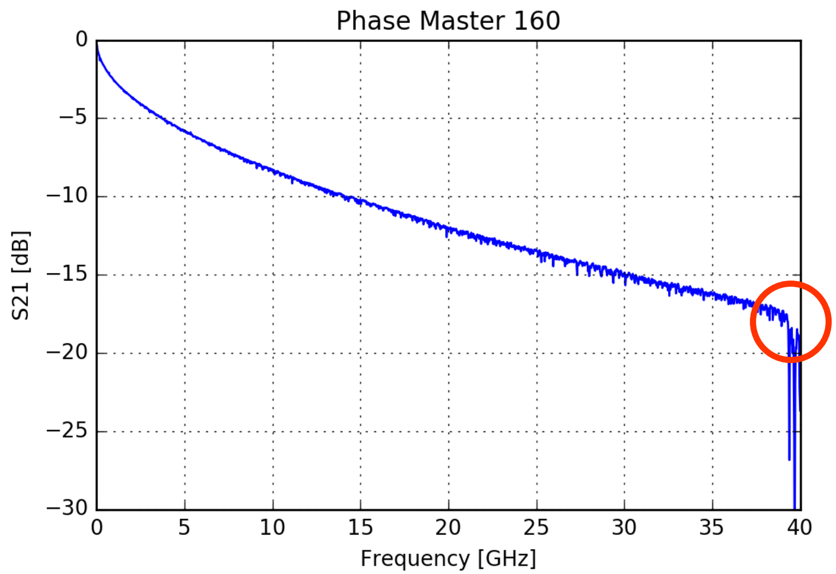
→ Shielding effectiveness more than 120 dB @ 26.5GHz

# Periodic Structures

At higher frequency periodic structures of the shielding and stranded inner wire can be the reason for unexpected behaviour.

| | LL 142 | PM 160 |
|---|---|---|
| Centre conductor diameter | 1.30 mm | 1.11 mm |
| Dielectric diameter | 3.68 mm | 2.89 mm |
| Permittivity | 1.54 | 1.32 |
| TE11 cut-off frequency | 31.69 GHz | 42.54 GHz |



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# Kink Protection

The most sensitive part on the cable is where the coax-cabel is assembled with the connector.

The strain should be minimised with a prober kink protection.

1 Good kink protection

2 Simple kink protection

3 No kink protection

1

2

3




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# Bend Radius

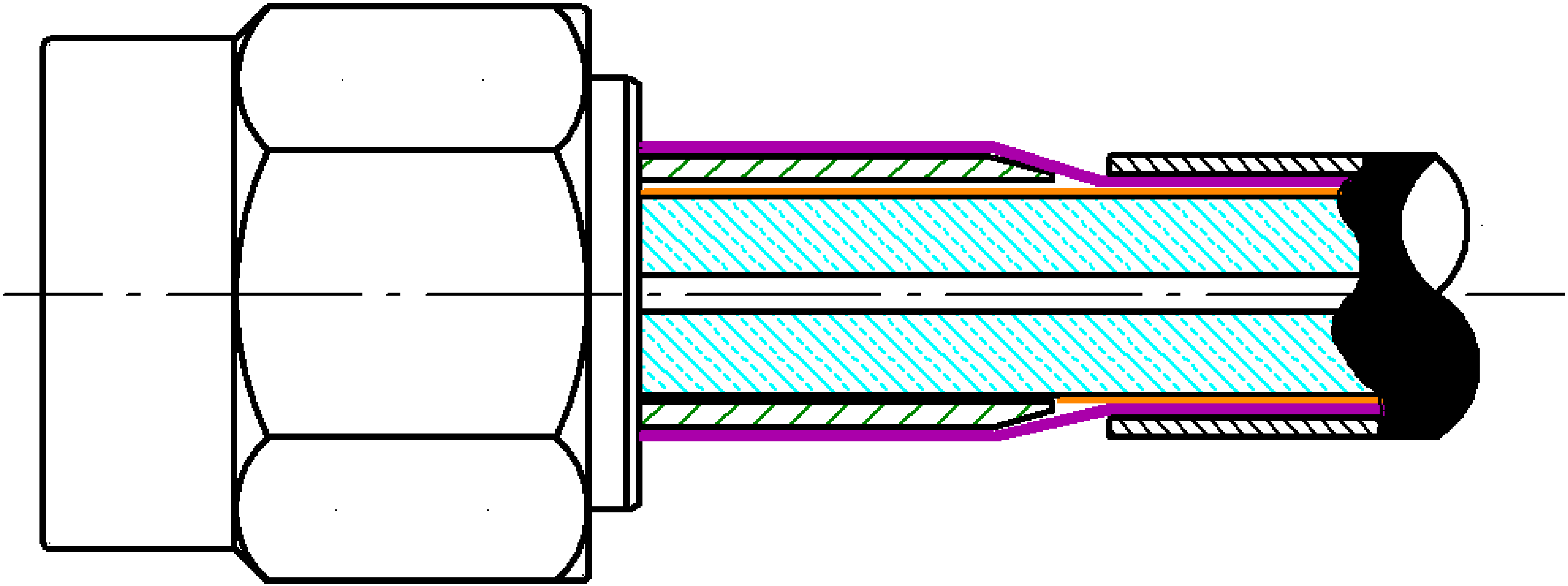
Coax-cable don't like to be bend with a small radius except of exceptions.

In no case torsion!

| SPECIFICATIONS | | 160 |
|---|---|---|
| **Cable Designator** | | **84** |
| Diameter (in/mm) | | 0.160/4.06 |
| Operating Frequency (Max, GHz) | | 40 |
| Attenuation–Max @ 2 GHz (dB/ft) | | 0.150 |
| Attenuation–Max @ 10 GHz (dB/ft) | | 0.347 |
| Attenuation–Max @ 18 GHz (dB/ft) | | 0.474 |
| Attenuation–Max @ 26.5 GHz (dB/ft) | | 0.585 |
| Attenuation–Max @ 32 GHz (dB/ft) | | 0.648 |
| Attenuation–Max @ 40 GHz (dB/ft) | | 0.732 |
| Power Handling – Avg Power in Watts @ 1 GHz | | 527 |
| Phase Stability vs. Flexure† (@ 18 GHz, nom) | | ±3.5° |
| Shielding Effectiveness–Min‡ (dB @ 1 GHz) | | > –90 |
| Typical VSWR (2 straight connectors) | | 1.28 to 40 GHz |
| Min Bend Radius (in/mm) | Static | 0.75/19.1 |
| | Dynamic | 1.5/38.2 |
| Connector Retention to 18 GHz, pull (lbs/kg) | | 20/9.07 |
| Velocity of Propagation (%) | | 87.0 |
| Weight (grams/ft & /m) | | 12.12/39.76 |
| Operating Temperature Range (°C) | | –55 to +125 |

| 141 |
|---|
| **920** |
| 0.160/4.06 |
| 26.5 |
| 0.60 |
| 0.76 |
| – |
| –90 or better |
| Available (except Express) |
| 0.320/8.13 |
| 40/18.14 |
| 15/6.80 |
| 13.4/43.95 |
| –54 to +125 |

# Crimp Connector



# Humidity

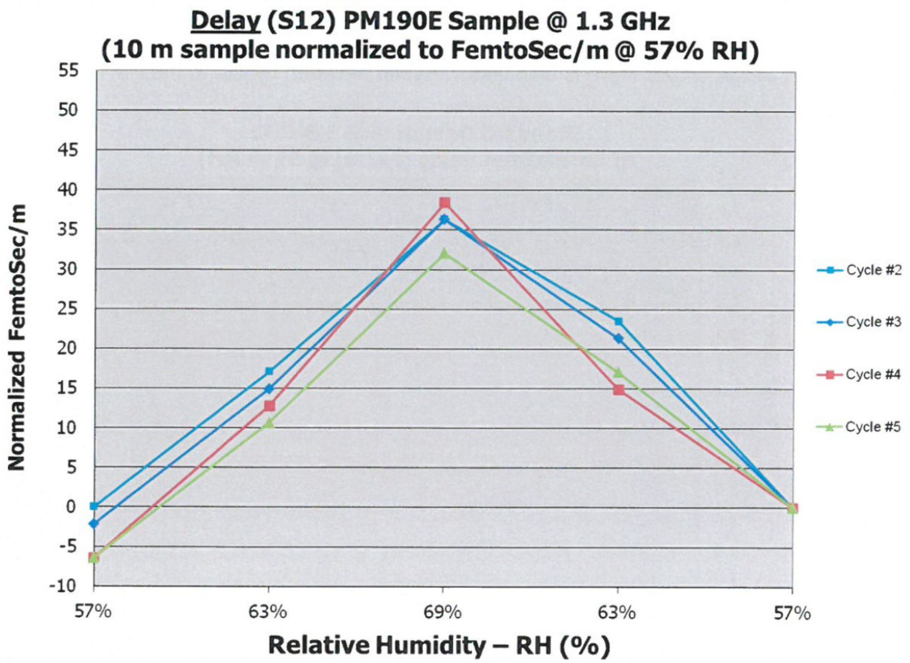
$$a = \frac{(\frac{c}{v})^2 - \epsilon_{r\_PTFE}}{\epsilon_{r\_Air} - \epsilon_{r\_PTFE}} \quad (19)$$

$$\epsilon_r = a \cdot \epsilon_{r\_Air} + b \cdot \epsilon_{r\_PTFE} \quad (20)$$

$$\Delta t = \frac{l}{c} \cdot (\sqrt{\epsilon_{r\_1}} - \sqrt{\epsilon_{r\_2}}) \quad (21)$$

| | | |
|---|---|---|
| a | : | Air amount |
| $\frac{v}{c_0}$ | : | Velocity of propagation 86% |
| $\epsilon_{r\_PTFE}$ | : | Permittivity of PTFE |
| $\epsilon_{r\_Air}$ | : | Permittivity of air |

| Humidity | $\varepsilon_r$ - 1 | Δt [fs/m] |
|---|---|---|
| 0% | 5.287 $10^{-4}$ | 97.4 |
| 36% | 6.019 $10^{-4}$ | 27.3 |
| 50% | 6.304 $10^{-4}$ | 0 |
| 70% | 6.710 $10^{-4}$ | -38.9 |
| 100% | 7.320 $10^{-4}$ | -97.3 |





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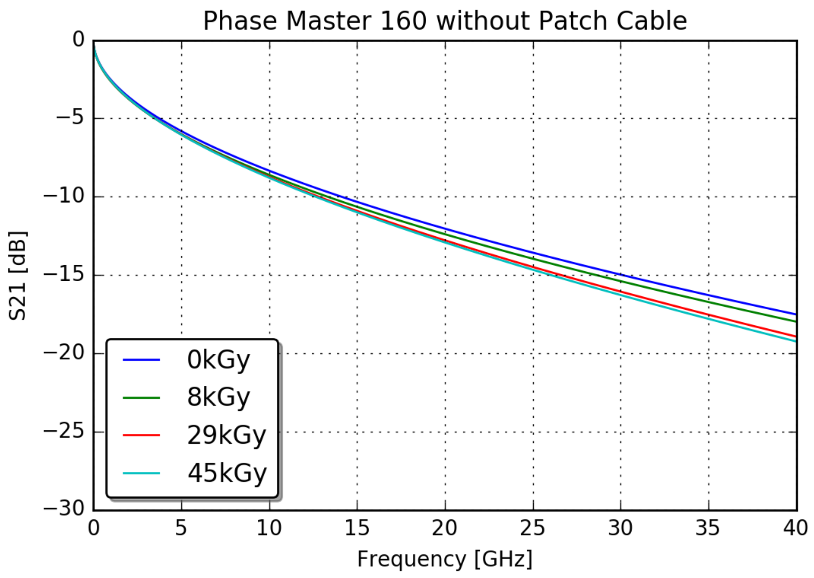
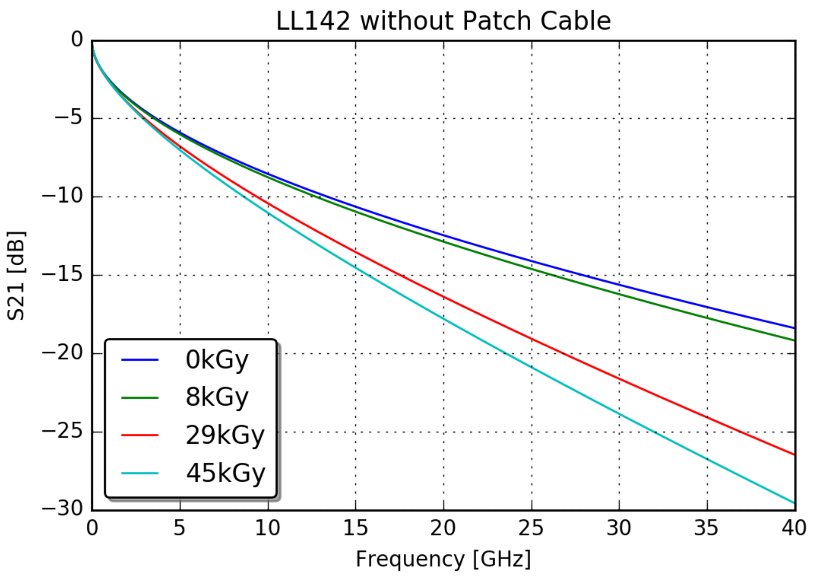
# Ionising Radiation

Ionising radiation break the long molecules of the PTFE polymer. If nearby another break new connection will happen, cross-links.
This change the material properties.



# Cable protection


Protection against light compression to running over with a car.



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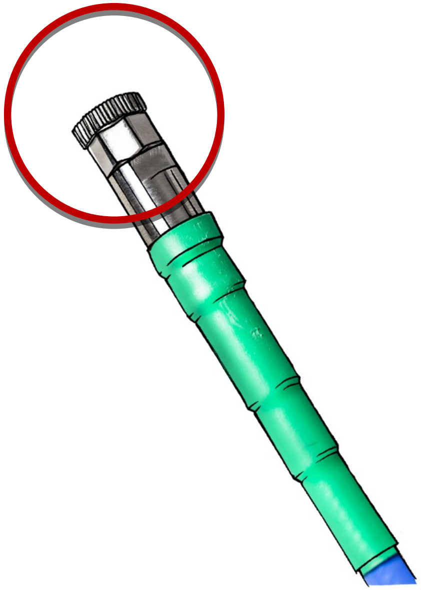
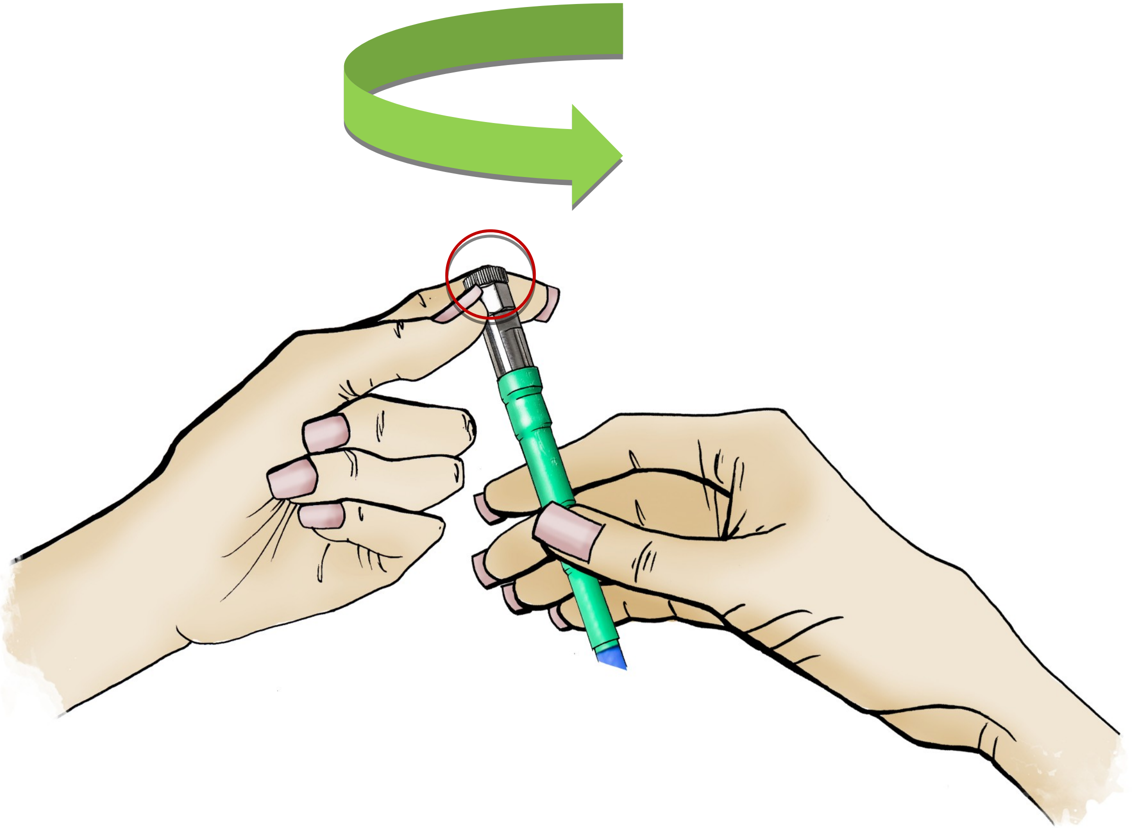
# Secure connection

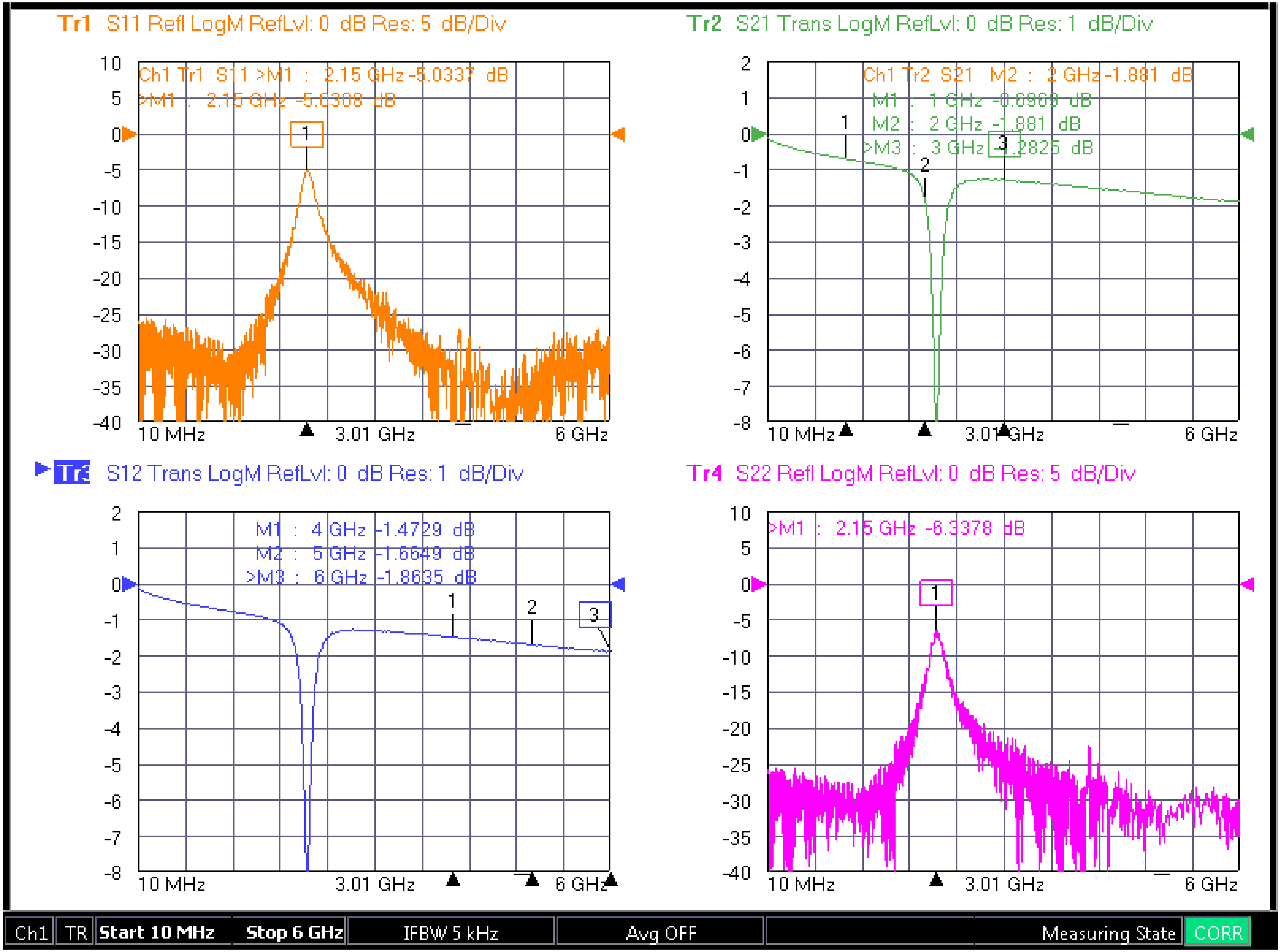




# Secure connection

Use the right torque spanner to fasten it.

# Secure connection



# Thank you for your attention!

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