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ITAINNOVA
INSTITUTO TECNOLÓGICO DE ARAGÓN

Update on EMC (grounding) Studies:
Noise propagation issues in PXD power cable

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OUTLINE

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1. Introduction

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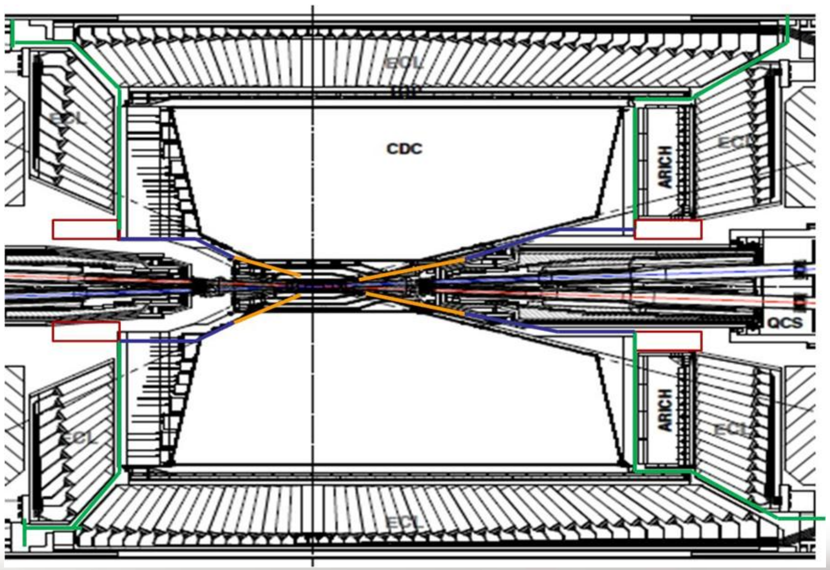
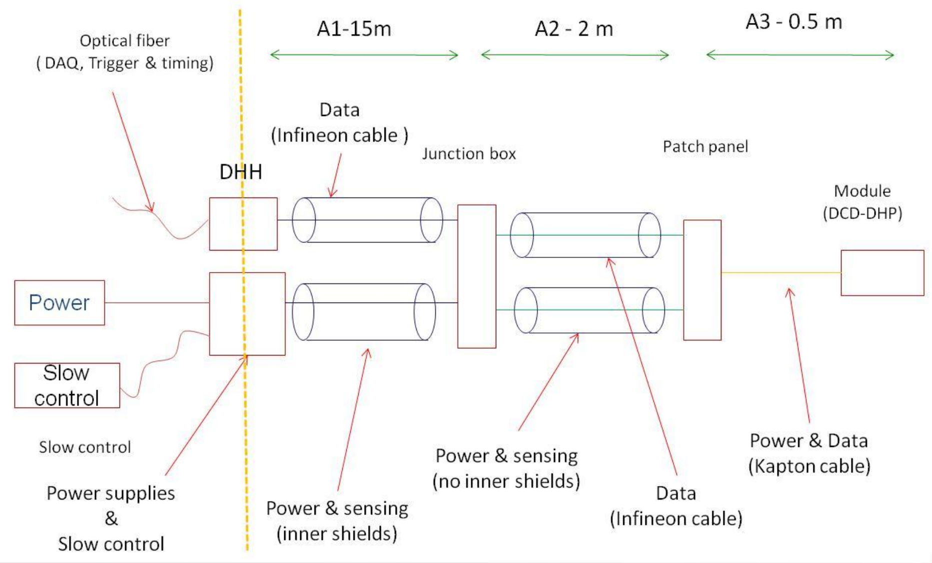
- The main goal of the EMC project is to characterize the electromagnetic environment of PXD to minimize noise emissions and susceptibility of PXD system.
- The project has been divided into four working packages
  - **Grounding and shielding strategy for PXD**
  - **Conducted and Radiated Noise emissions test.**
    - **PS units & FEE**
  - **Noise propagation issues in power cables**
  - Immunity issues of PXD system.

1. Introduction

- **The noise propagation studies has been focused on power cable 1**
  - Low impedance connection to “external” world .
  - It crosses all the experiment (15 meter long aprox.).
- **Three tasks have been planned in order to evaluate this cable**
  - Development of MTL model of PXD cable based on MATLAB code.
  - Characterization of PXD power cable 1: L,C,R and G matrices
  - Characterization of CM , DM and shields transfer function of Power cable 1.





2. Cable Model

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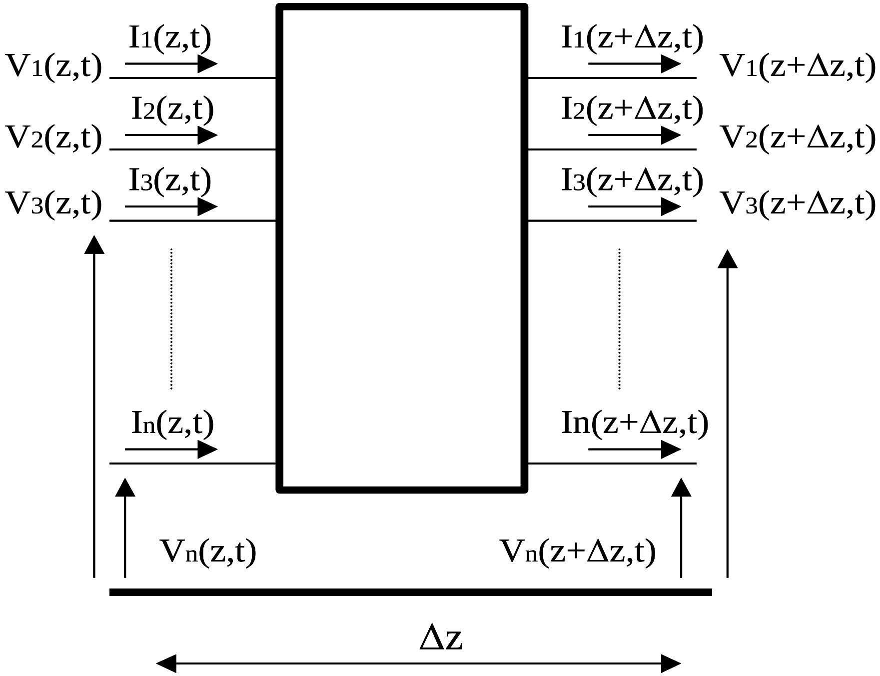
- The power cable is a very complex cable
- Power , Bias & sense
- Around 30 conductors
  - Internal & external shields
- Structure / STEER & ANLG
  - 3x18AWG
  - 1x14AWG
  - 1x20AWG
  - 4x2x26AWG
  - 1x18 AWG
  - 4x2x26AWG
  - 4x2x26AWG

2.1 Cable Model: MTL

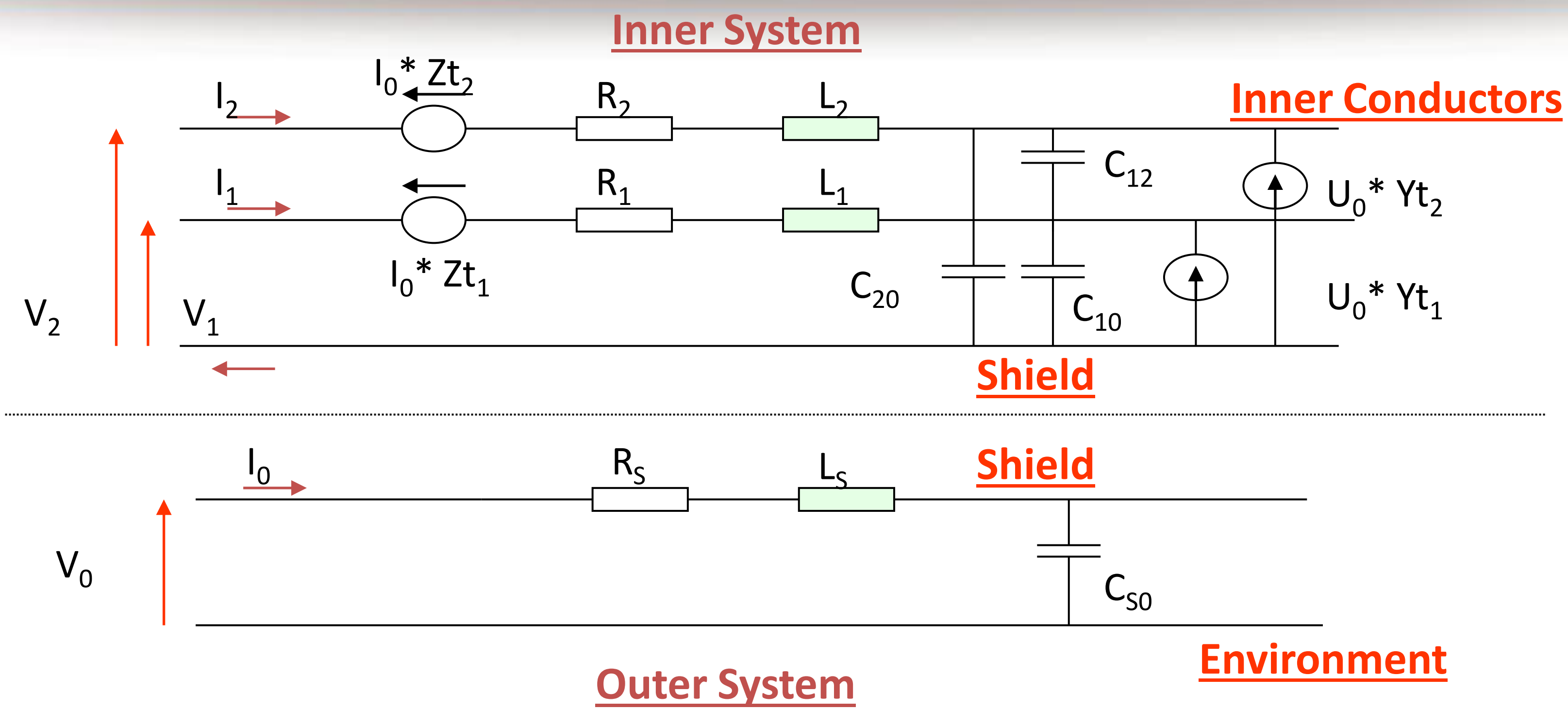
- Cable performance has been evaluated using Multi-conductor Transmission Line Theory (MTL).
- It assumes several issues:
  - Propagation mode: TEM
    - R,L,C,G line parameters matrices per unit length
  - V,I voltage & current vectors
- Solution:
  - Terminal Boundary conditions
    - Load impedances
    - Source impedances
  - Frequency domain



$$\frac{\partial}{\partial z}V(z,t) = -R\,I(z,t) - L\frac{\partial}{\partial t}I(z,t)$$

$$\frac{\partial}{\partial z}I(z,t) = -G\,V(z,t) - C\frac{\partial}{\partial t}V(z,t)$$

2.1 Cable Model: MTL



$$\frac{\partial}{\partial z}V(z,t) = -R\,I(z,t) - L\frac{\partial}{\partial t}I(z,t) + Zt \cdot Io(z,t)$$

$$\frac{\partial}{\partial z}I(z,t) = -GV(z,t) - C\frac{\partial}{\partial t}V(z,t) + Yt \cdot Uo(z,t)$$

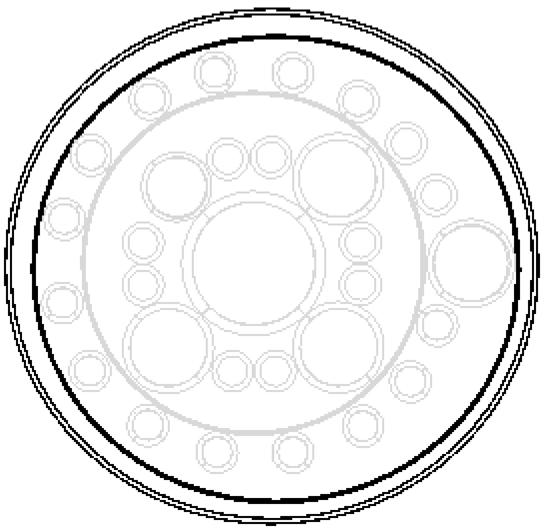
$$Zt = Zd(\omega) + j.(Mh \pm Mb)$$

Define the amount of noise coupled into the internal conductors (Yt & G neglectable)

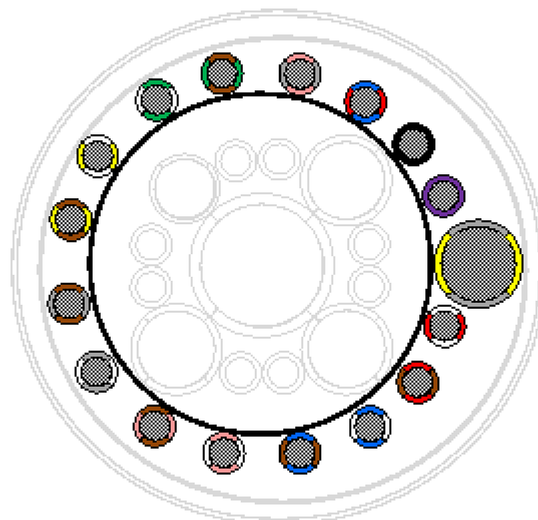
➢ **A MATLAB program has been developed in order to solve numerically these equations**
- **It has been validated with real measurements**

2.2 Cable Model: Parameters

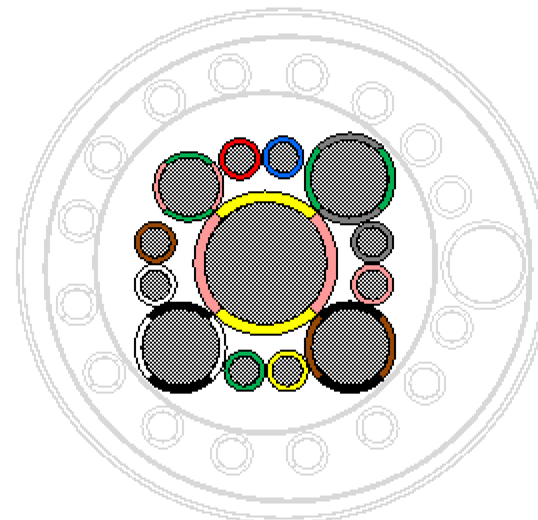
- The MTL model divided the cable into three systems



External system



Steering system



Anlg/Dig system

2.2 Cable Model: Parameters

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- Cable measurement & matrix calculation – **Long procedure**
  - L, C, & R matrix measurements (uncertainties included)
    - External system: Matrix 1x1 for each L,C,R
    - Steering system: Matrix 18x18 for each L,C,R
    - Analogue/Digital system: Matrix 13x13 for each L,C,R

Lij (H/m)

Anlg

1,7917E-07	3,5785E-08	3,7501E-08	1,7984E-08	7,9249E-09	1,408E-08	1,267E-08	9,8576E-09	1,6225E-08	2,1432E-08	4,1599E-08	4,086E-08	5,5392E-08
3,5785E-08	3,4656E-07	7,4653E-08	4,5076E-08	1,5116E-08	2,4883E-08	1,2847E-08	1,0294E-08	1,4994E-08	1,2139E-08	1,5382E-08	1,6253E-08	5,9592E-08
3,7501E-08	7,4653E-08	3,4569E-07	4,2379E-08	1,2486E-08	2,1652E-08	1,0223E-08	8,9848E-09	1,2081E-08	1,1579E-08	1,6257E-08	1,6434E-08	5,8334E-08
1,7984E-08	4,5076E-08	4,2379E-08	2,2074E-07	4,3475E-08	5,2261E-08	1,8428E-08	1,1614E-08	1,8097E-08	1,8808E-08	1,4394E-08	1,5254E-08	5,7651E-08
7,9249E-09	1,5116E-08	1,2486E-08	4,3475E-08	3,6977E-07	9,7355E-08	3,993E-08	2,87E-08	2,9359E-08	1,2606E-08	1,22E-08	1,1378E-08	5,5355E-08
1,408E-08	2,4883E-08	2,1652E-08	5,2261E-08	9,7355E-08	3,8212E-07	4,4659E-08	3,7067E-08	3,9511E-08	1,2379E-08	2,0964E-08	2,238E-08	6,3859E-08
1,267E-08	1,2847E-08	1,0223E-08	1,8428E-08	3,993E-08	4,4659E-08	1,8113E-07	4,3781E-08	4,5767E-08	1,7252E-08	9,7872E-09	1,083E-08	5,5222E-08
9,8576E-09	1,0294E-08	8,9848E-09	1,1614E-08	2,87E-08	3,7067E-08	4,3781E-08	3,8317E-07	9,912E-08	4,3345E-08	1,8813E-08	2,3157E-08	5,418E-08
1,6225E-08	1,4994E-08	1,2081E-08	1,8097E-08	2,9359E-08	3,9511E-08	4,5767E-08	9,912E-08	3,8546E-07	4,8509E-08	1,9333E-08	2,1192E-08	5,9035E-08
2,1432E-08	1,2139E-08	1,1579E-08	1,8808E-08	1,2606E-08	1,2379E-08	1,7252E-08	4,3345E-08	4,8509E-08	1,823E-07	3,8448E-08	3,9629E-08	5,8874E-08
4,1599E-08	1,5382E-08	1,6257E-08	1,4394E-08	1,22E-08	2,0964E-08	9,7872E-09	1,8813E-08	1,9333E-08	3,8448E-08	3,5417E-07	8,2883E-08	6,1191E-08
4,086E-08	1,6253E-08	1,6434E-08	1,5254E-08	1,1378E-08	2,238E-08	1,083E-08	2,3157E-08	2,1192E-08	3,9629E-08	8,2883E-08	3,6017E-07	6,2036E-08
5,5392E-08	5,9592E-08	5,8334E-08	5,7651E-08	5,5355E-08	6,3859E-08	5,5222E-08	5,418E-08	5,9035E-08	5,8874E-08	6,1191E-08	6,2036E-08	2,2405E-07

Lij (H/m)

Steering

3,3305E-07	6,4643E-08	2,1536E-08	2,6152E-08	1,95E-08	1,5983E-08	2,0811E-08	2,0841E-08	1,6444E-08	1,944E-08	1,8403E-08	2,2339E-08	2,136E-08	1,9611E-08	2,1804E-08	2,3855E-08	2,2012E-08	2,8946E-08
6,4643E-08	3,2541E-07	3,0127E-08	2,9758E-08	1,9849E-08	1,3785E-08	2,0071E-08	2,1171E-08	2,0063E-08	7,96E-09	8,4492E-09	1,7848E-08	1,4164E-08	1,5483E-08	1,5428E-08	1,7865E-08	1,8094E-08	2,7957E-08
2,1536E-08	3,0127E-08	3,0856E-07	4,871E-08	1,6895E-08	1,7397E-08	1,6101E-08	1,5371E-08	1,575E-08	1,4455E-08	1,4588E-08	1,6748E-08	1,7062E-08	1,4825E-08	1,7639E-08	1,7269E-08	3,8226E-09	2,4797E-08
2,6152E-08	2,9758E-08	4,871E-08	3,121E-07	1,7688E-08	1,6305E-08	1,2428E-08	1,6748E-08	1,7724E-08	1,68E-08	1,5804E-08	1,6576E-08	1,6363E-08	1,5849E-08	1,4787E-08	1,91E-08	2,7106E-09	2,629E-08
1,95E-08	1,9849E-08	1,6895E-08	1,7688E-08	3,0832E-07	4,6129E-08	1,8808E-08	1,9976E-08	1,515E-08	1,2073E-08	1,3361E-08	1,4317E-08	1,7034E-08	1,3817E-08	1,5534E-08	1,7942E-08	3,9545E-09	2,5465E-08
1,5983E-08	1,3785E-08	1,7397E-08	1,6305E-08	4,6129E-08	3,0375E-07	1,749E-08	1,7172E-08	1,3778E-08	1,272E-08	1,1146E-08	1,2823E-08	1,2672E-08	9,5374E-09	1,1403E-08	1,2789E-08	1,3079E-09	2,2682E-08
2,0811E-08	2,0071E-08	1,6101E-08	1,2428E-08	1,8808E-08	1,749E-08	3,0662E-07	4,7619E-08	1,8386E-08	1,7634E-08	1,3962E-08	1,5036E-08	1,4644E-08	1,2752E-08	1,3803E-08	1,6205E-08	2,867E-09	2,5027E-08
2,0841E-08	2,1171E-08	1,5371E-08	1,6748E-08	1,9976E-08	1,7172E-08	4,7619E-08	3,0937E-07	1,9607E-08	2,1322E-08	1,5381E-08	1,578E-08	1,6331E-08	1,5151E-08	1,5373E-08	1,7186E-08	4,9731E-09	2,4011E-08
1,6444E-08	2,0063E-08	1,575E-08	1,7724E-08	1,515E-08	1,3778E-08	1,8386E-08	1,9607E-08	3,1378E-07	4,8915E-08	2,055E-08	2,163E-08	1,9628E-08	1,5591E-08	1,5785E-08	1,7787E-08	5,9969E-09	2,3802E-08
1,944E-08	7,96E-09	1,4455E-08	1,68E-08	1,2073E-08	1,272E-08	1,7634E-08	2,1322E-08	4,8915E-08	3,1217E-07	1,995E-08	2,2534E-08	1,709E-08	1,3952E-08	1,506E-08	1,6791E-08	4,5375E-09	2,2087E-08
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2,2339E-08	1,7848E-08	1,6748E-08	1,6576E-08	1,4317E-08	1,2823E-08	1,5036E-08	1,578E-08	2,163E-08	2,2534E-08	5,349E-08	3,1671E-07	2,4048E-08	2,2794E-08	1,767E-08	1,8498E-08	8,1846E-09	1,6768E-08
2,136E-08	1,4164E-08	1,7062E-08	1,6363E-08	1,7034E-08	1,2672E-08	1,4644E-08	1,6331E-08	1,9628E-08	1,709E-08	2,1868E-08	2,4048E-08	3,228E-07	5,4221E-08	2,4583E-08	2,7561E-08	7,0623E-09	2,717E-08
1,9611E-08	1,5483E-08	1,4825E-08	1,5849E-08	1,3817E-08	9,5374E-09	1,2752E-08	1,5151E-08	1,5591E-08	1,3952E-08	2,0123E-08	2,2794E-08	5,4221E-08	3,1666E-07	2,4775E-08	2,5238E-08	4,783E-09	2,454E-08
2,1804E-08	1,5428E-08	1,7639E-08	1,4787E-08	1,5534E-08	1,1403E-08	1,3803E-08	1,5373E-08	1,5785E-08	1,506E-08	1,5523E-08	1,767E-08	2,4583E-08	2,4775E-08	3,285E-07	6,037E-08	1,607E-08	2,4562E-08
2,3855E-08	1,7865E-08	1,7269E-08	1,91E-08	1,7942E-08	1,2789E-08	1,6205E-08	1,7186E-08	1,7787E-08	1,6791E-08	1,6119E-08	1,8498E-08	2,7561E-08	2,5238E-08	6,037E-08	3,2991E-07	1,909E-08	2,6926E-08
2,2012E-08	1,8094E-08	3,8226E-09	2,7106E-09	3,9545E-09	1,3079E-09	2,867E-09	4,9731E-09	5,9969E-09	4,5375E-09	5,5114E-09	8,1846E-09	7,0623E-09	4,783E-09	1,607E-08	1,909E-08	1,5664E-07	1,6992E-08
2,8946E-08	2,7957E-08	2,4797E-08	2,629E-08	2,5465E-08	2,2682E-08	2,5027E-08	2,4011E-08	2,3802E-08	2,2087E-08	1,7006E-08	1,6768E-08	2,717E-08	2,454E-08	2,4562E-08	2,6926E-08	1,6992E-08	5,2907E-08

External

Lij (H/m)
0.159E-6

3. Noise propagation studies

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- Several noise sources are implemented in order to study the effect of a specific type of noise in the cable
  - CM noise generated by PS
  - DM (ripple)noise generated by PS
  - Shield currents
- Terminal connections on both sides of the cables are included in the model (source terminal and load terminal)
  - Load & source impedances defined by input / output filters
  - CM impedances - normalized to 150 Ω
  - Sense impedances (10 kΩ)
- Frequency range 100 kHz to 100 MHz
- 100 samples simulated (Uncertainties – Monte Carlo)
  - Only the average simulated curves are shown

3. Noise propagation studies

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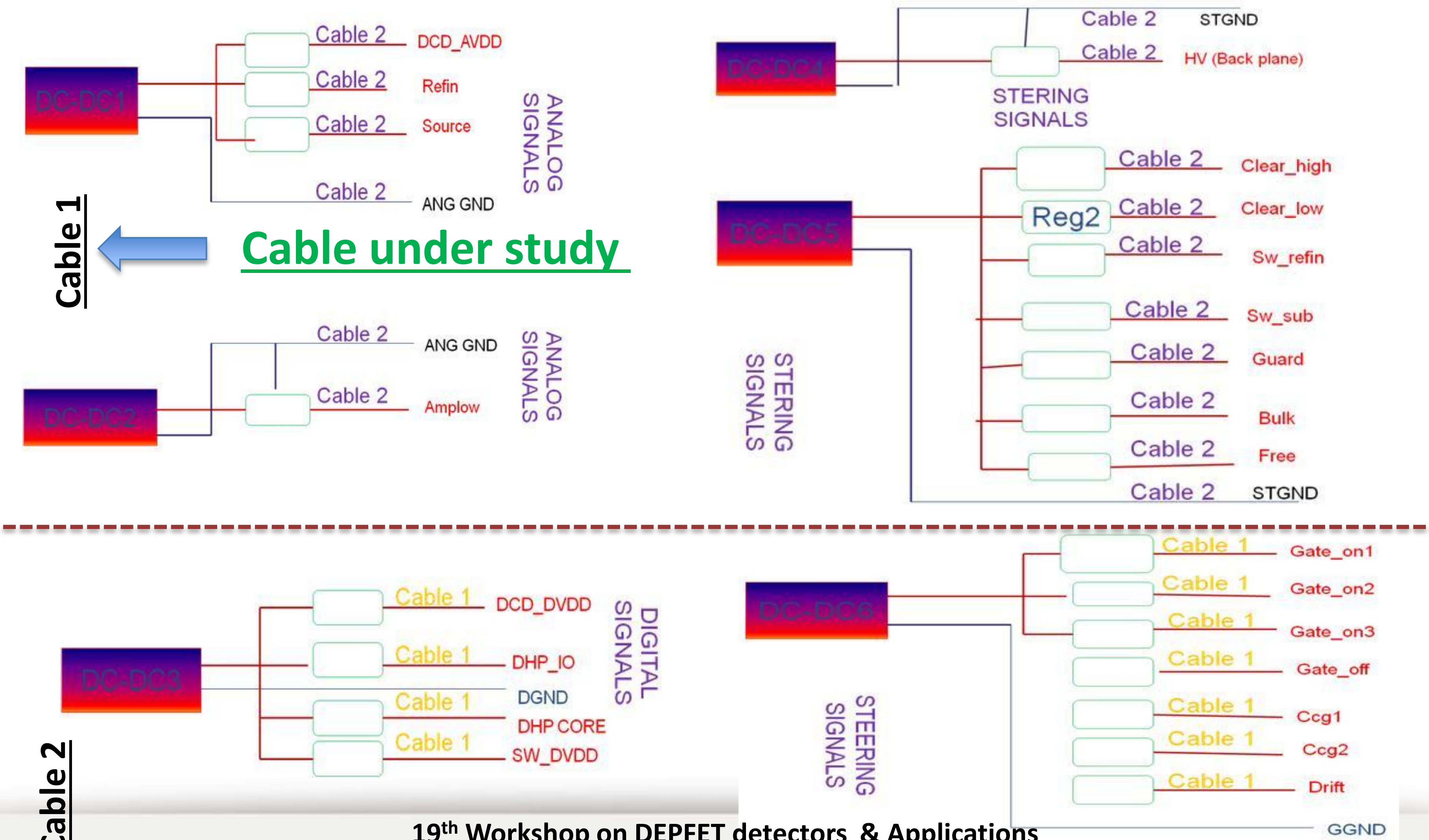
- **DEPFET power supply unit:**



3. Noise propagation studies

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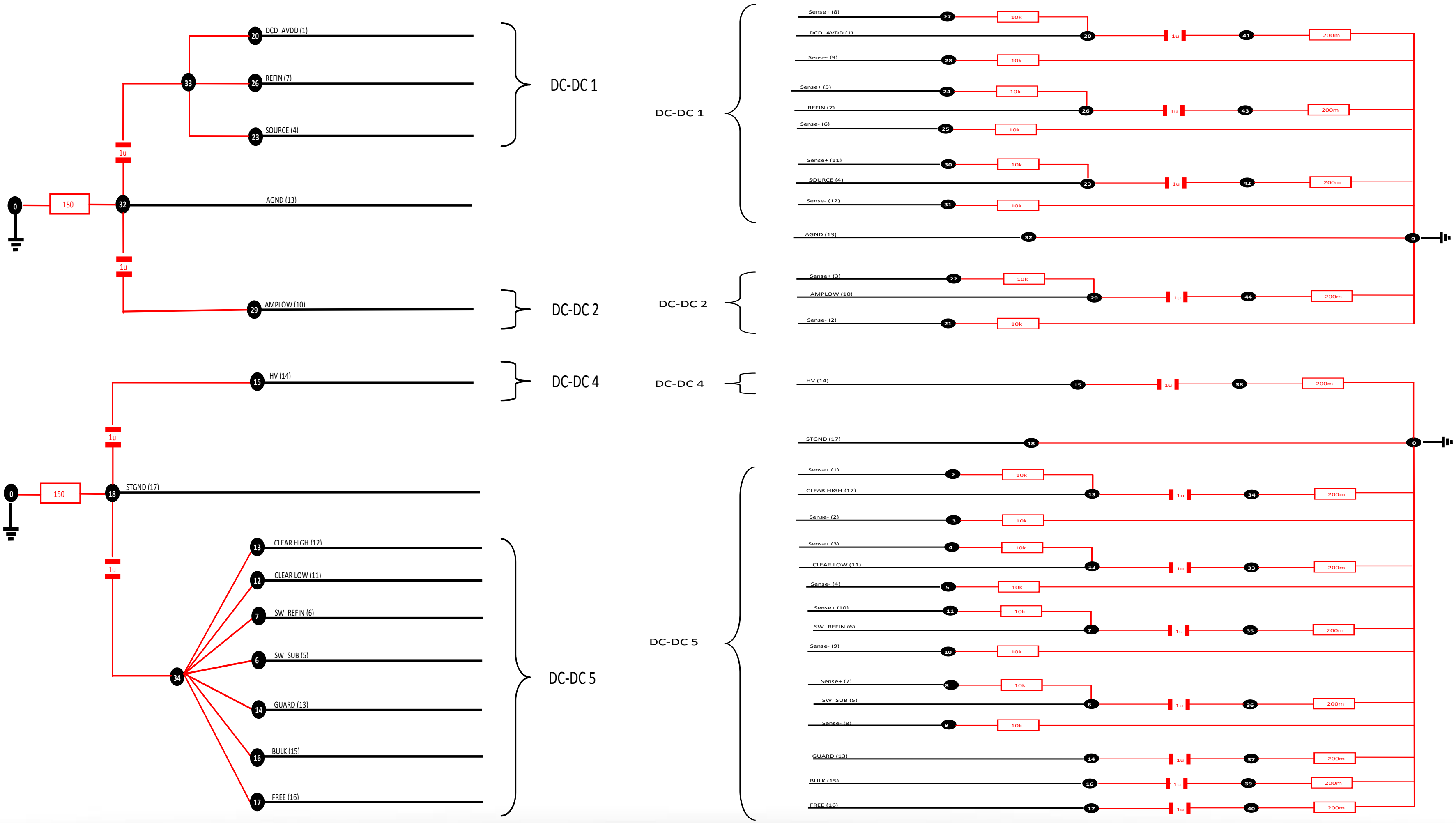
- DEPFET PS and LOAD is complex.

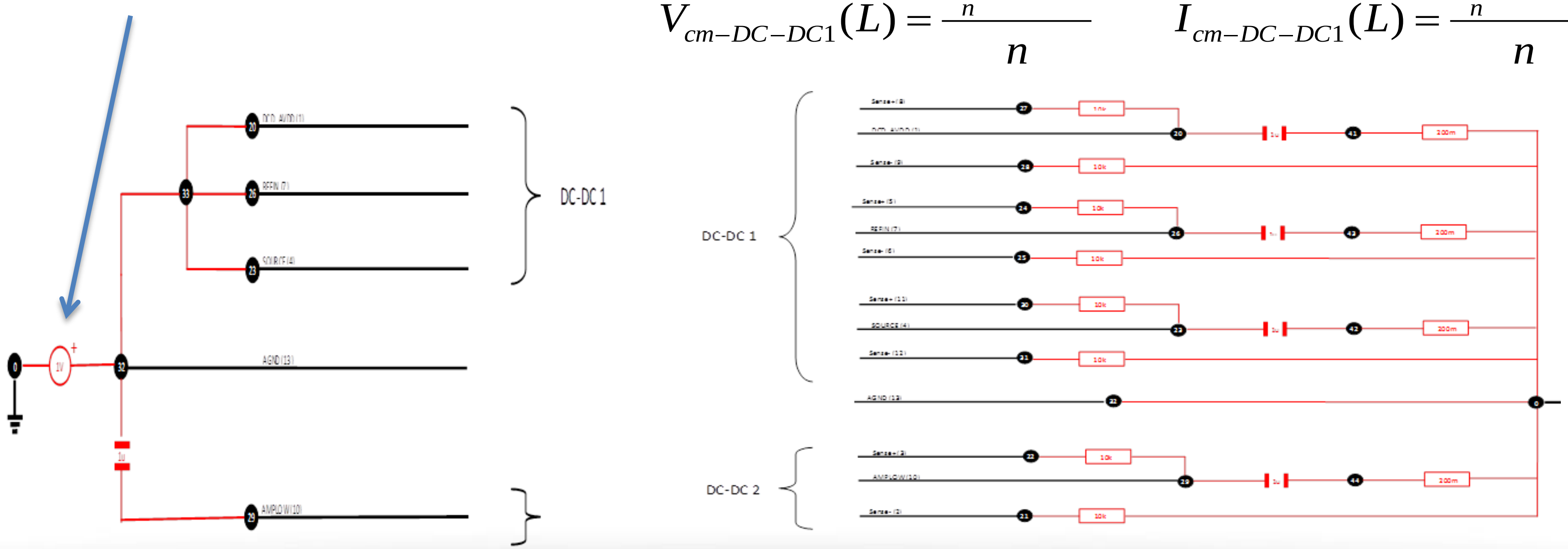


3.1 Noise propagation studies: CM noise from PS units

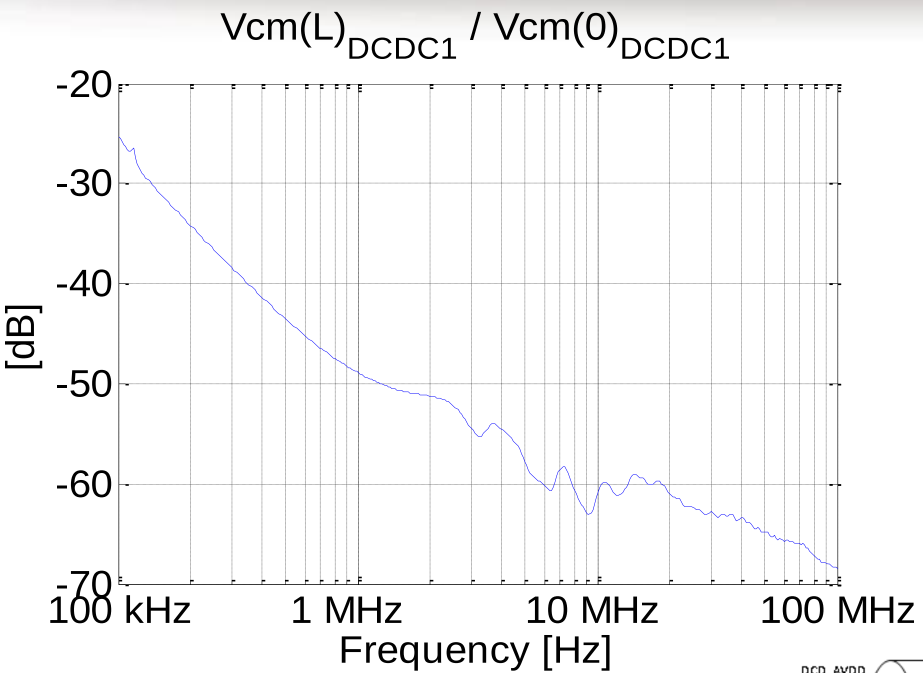
- The propagation of the CM injected by PS units is studied
  - Noise propagation through each line
  - Noise coupling among lines
- The CM voltage and current at the end of each line is measured and compared to the injected current

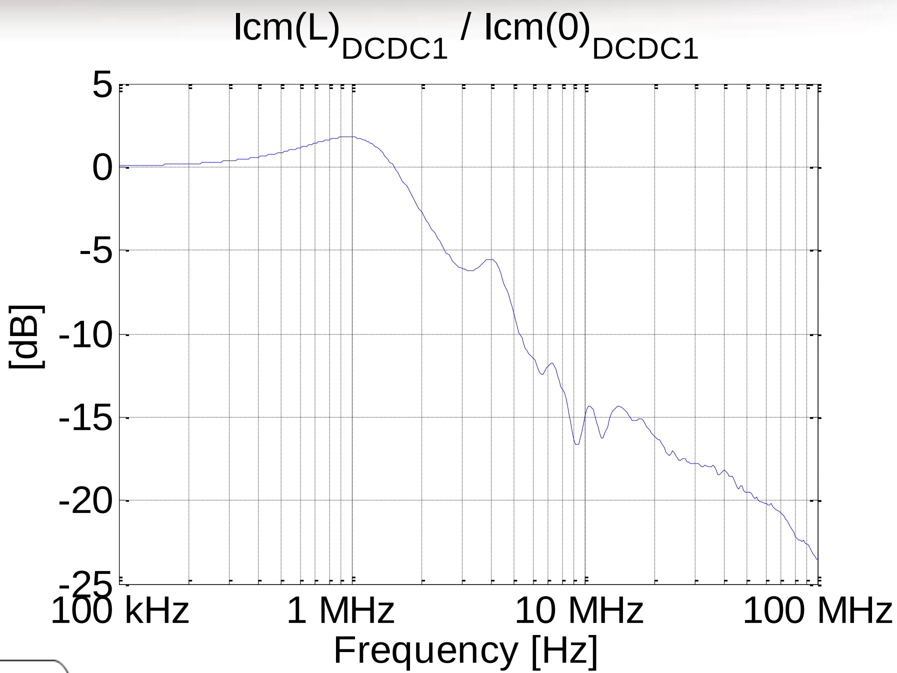
$$V_{cm-DC-DC1}(0)$$

$$\hat{V}_{cm-DC-DC1}(L) = \frac{\sum_{n} \hat{V}_i(L)}{n} \qquad \hat{I}_{cm-DC-DC1}(L) = \frac{\sum_{n} \hat{I}_i(L)}{n}$$

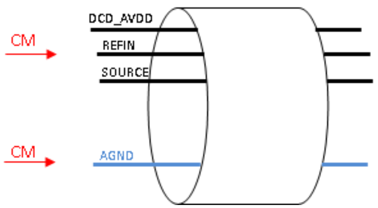


3.1 Noise propagation studies: CM noise from PS units





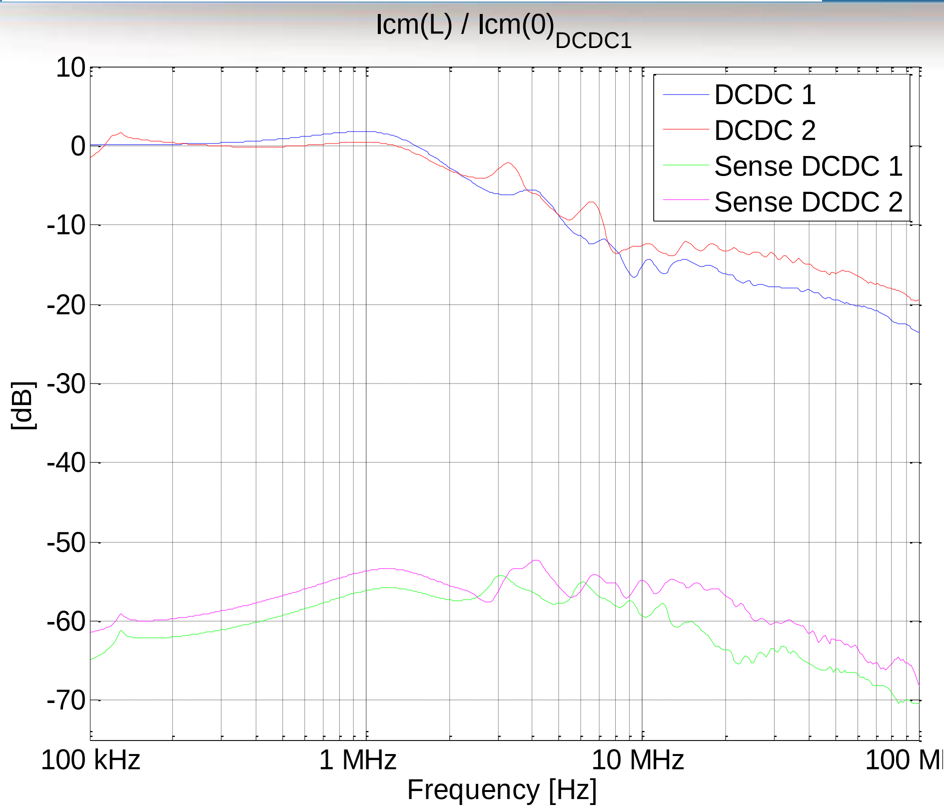
$$\hat{V}_{cm} = \frac{\hat{V}_{DCD\_AVDD} + \hat{V}_{REFIN} + \hat{V}_{SOURCE} + \hat{V}_{AGND}}{4}$$

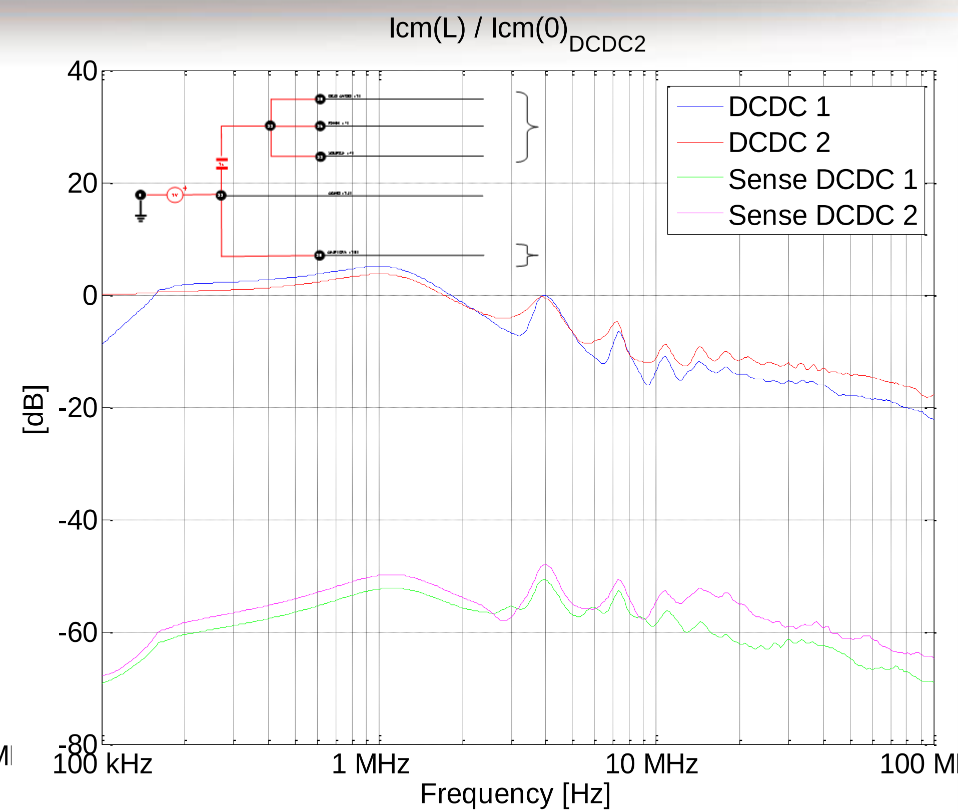


$$\hat{I}_{cm} = \frac{\hat{I}_{DCD\_AVDD} + \hat{I}_{REFIN} + \hat{I}_{SOURCE} + \hat{I}_{AGND}}{4}$$

- Voltage – Attenuation due to load filtering
- Current – Some amplification - But in general cabling resonance attenuated
  - Due to the high cable resistance
- Similar results to other DC-DC (2,3,4,5,6)

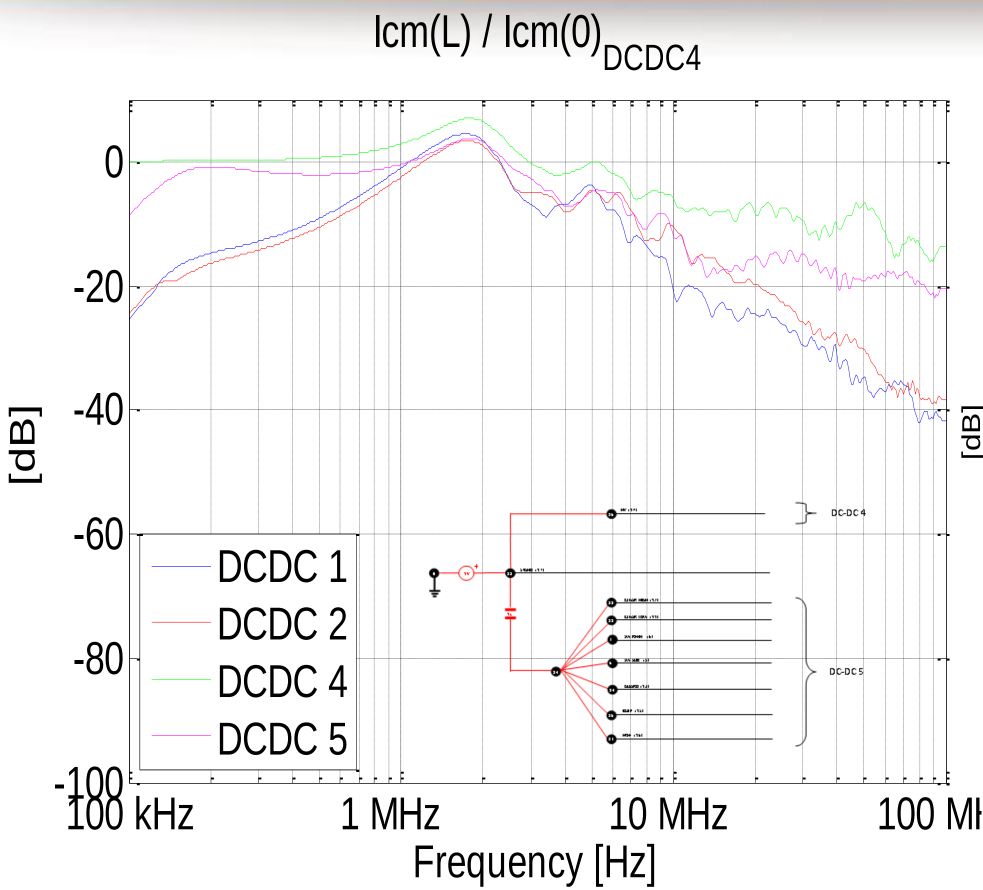
3.1 Noise propagation studies: CM noise from PS units

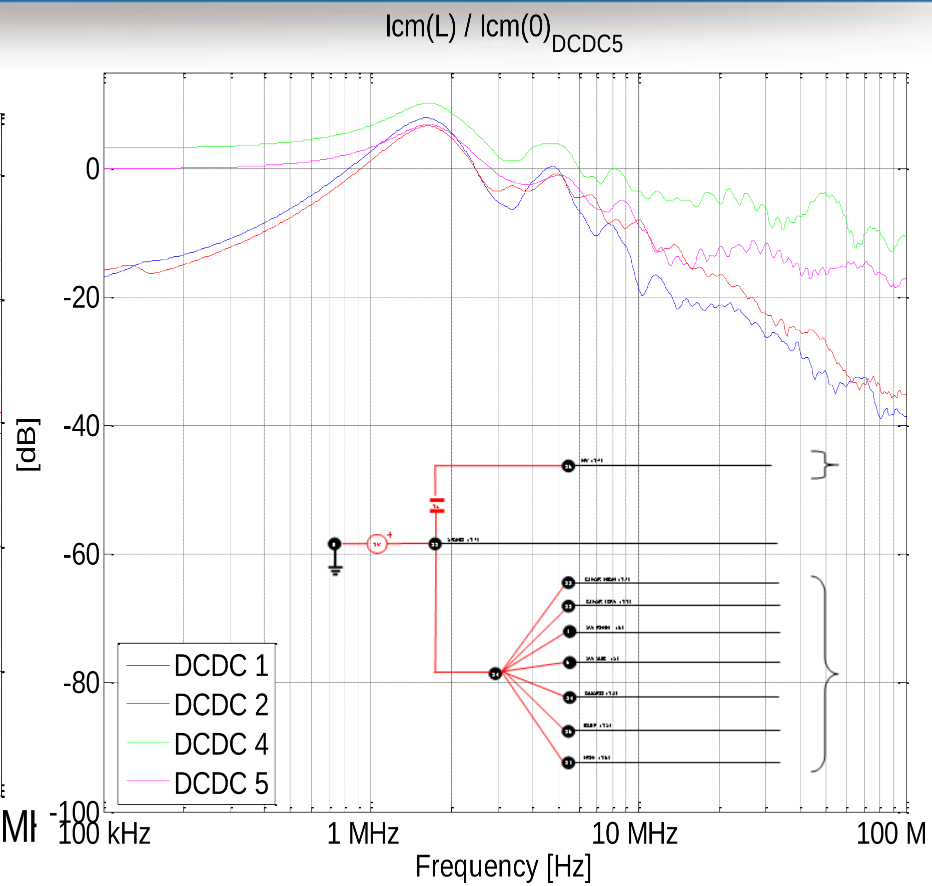




- Low noise coupling to sense lines
  - Due to the high impedance
- Similar coupling from DCDC1 to DC-DC2 /DC-DC2 to DC-DC1
  - Noise is defined by the common power return

3.1 Noise propagation studies: CM noise from PS units





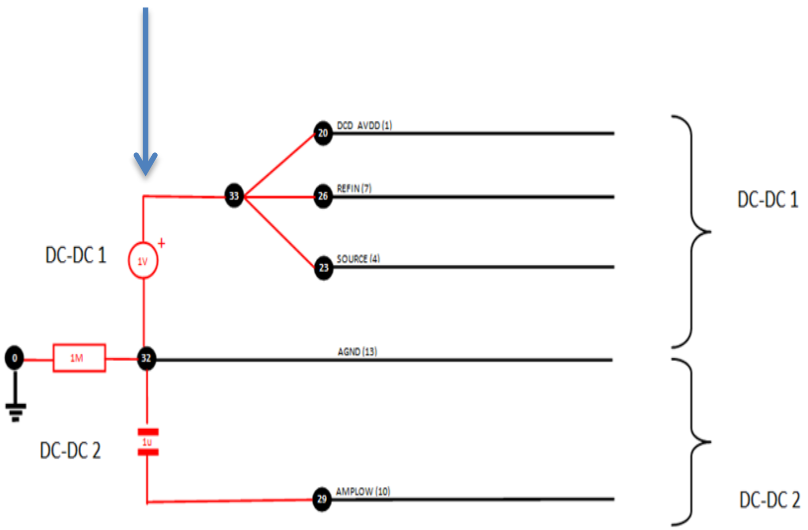
- Similar coupling from DCDC4 to DC-DC5 or DC-DC5 to DC-DC4
  - Noise is defined by the common power return
- Lower coupling level to cable connected to other DC-DC/f(freq)

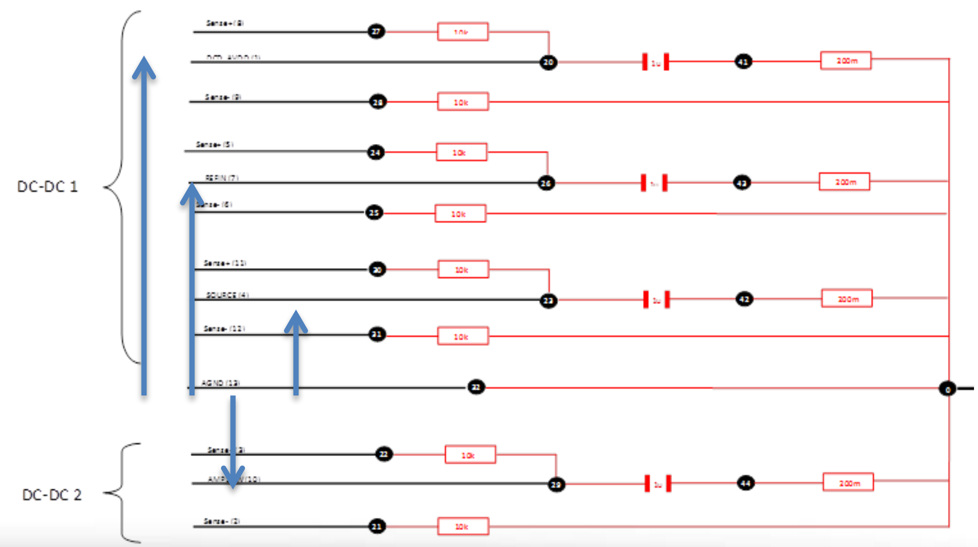
3.2 Noise propagation studies: DM noise from PS units (ripple)

- The propagation of the DM injected by PS units is studied
  - Noise propagation through each line
  - Noise coupling among lines
- It has an impact on ripple noise level at the entrance of the FEE
- The DM voltage and current at the end of each line is measured and compared to the injected current

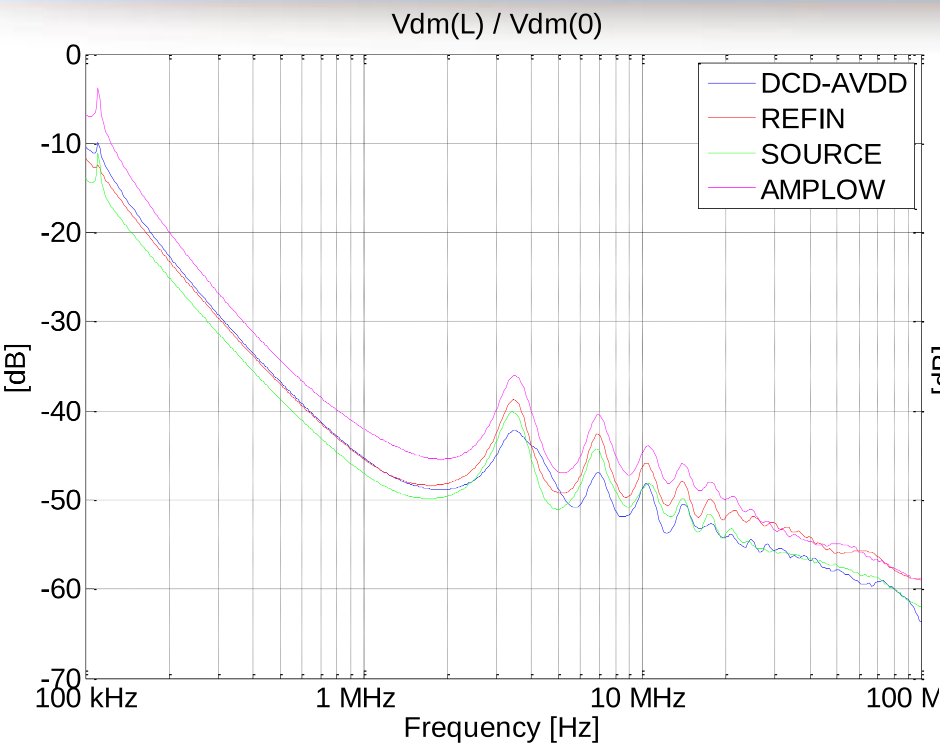
$V_{dm-DC-DC1}(0)$

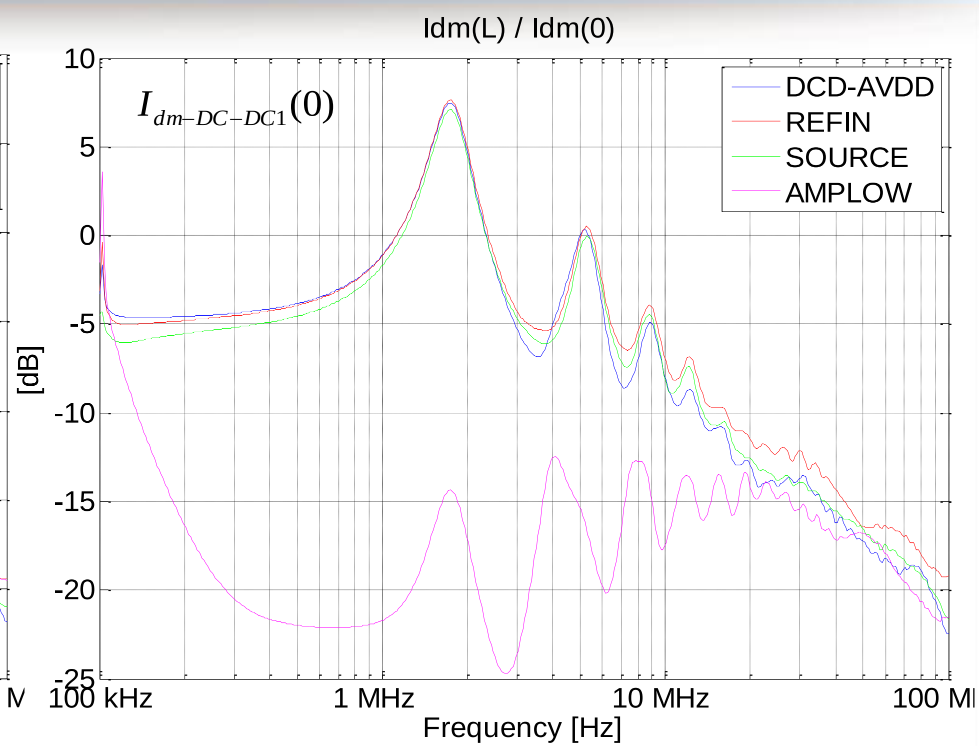
$$V_{dm} = \frac{V_{DM-DCD\_AVDD} - V_{AGND}}{2}, V_{dm_i}, \ldots$$





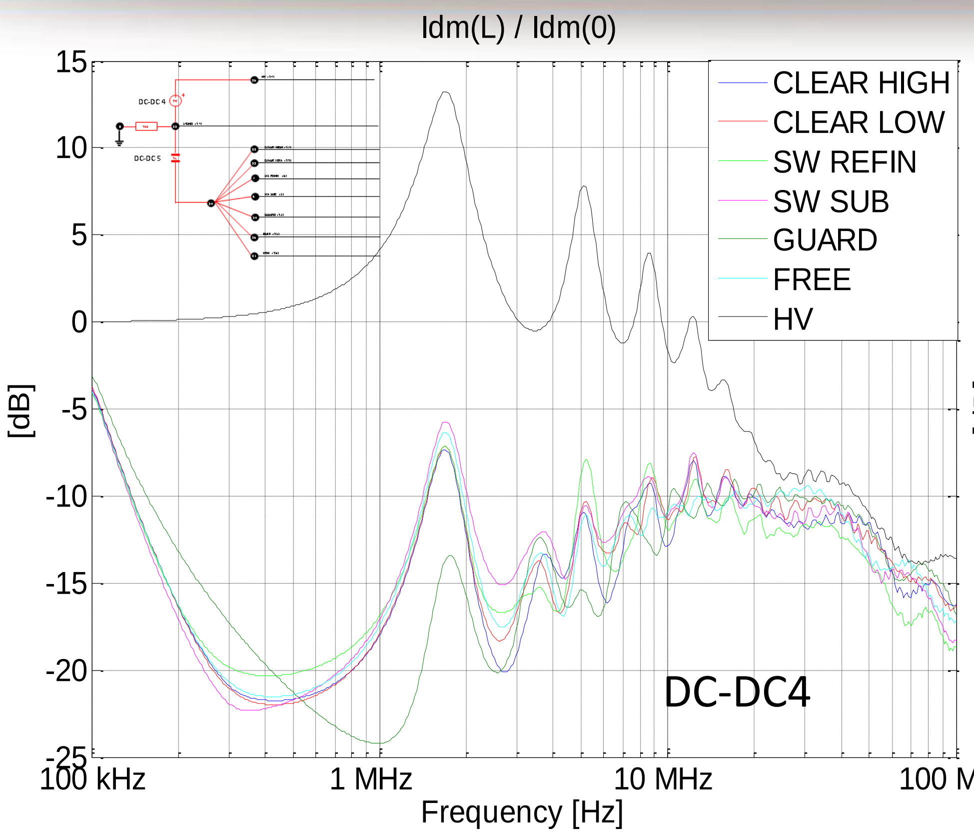
3.2 Noise propagation studies: DM noise from PS units (ripple)

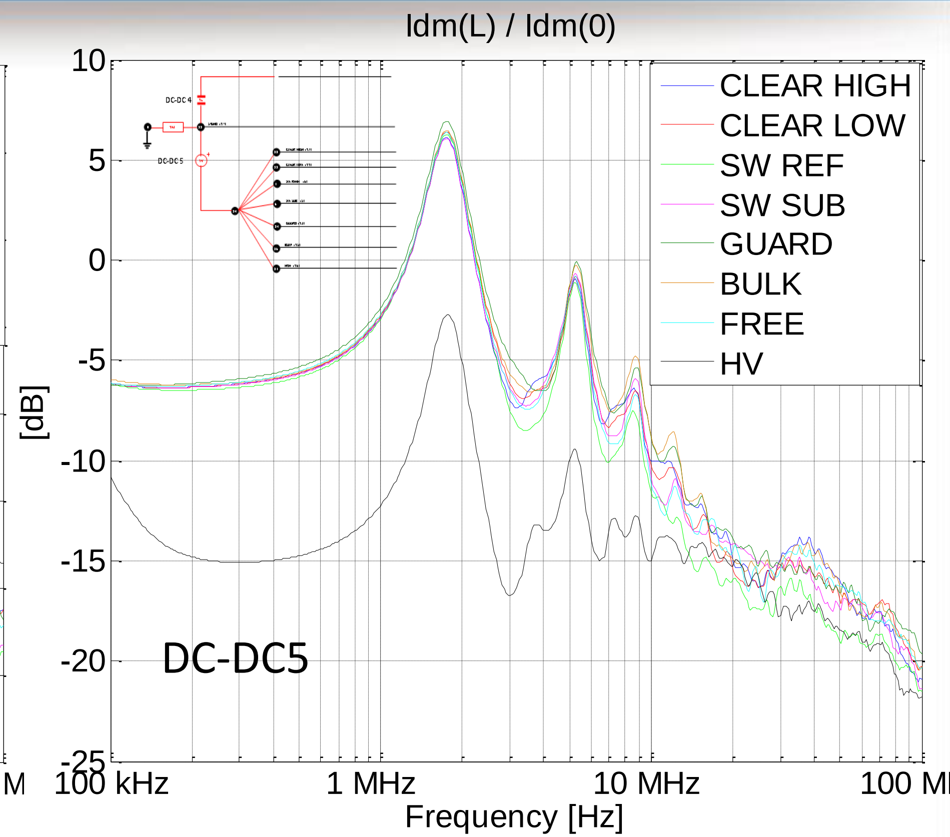




- Voltage – it is well attenuated due to DM capacitors
  - Similar voltage present in complementary lines - Common return
- Current is amplified but no radiation is expected due to return path compensation
  - Similar DM noise distribution in common lines
  - low DM current are expected in other systems in LF

3.2 Noise propagation studies: DM noise from PS units (ripple)





- Similar effects in other systems
  - Similar DM noise distribution in all common lines
  - Cross effect DC-DC4 / DC-DC5 is small
  - The coupling level into sense lines is low (similar to other cases)

3.3 Noise propagation studies: Shield currents

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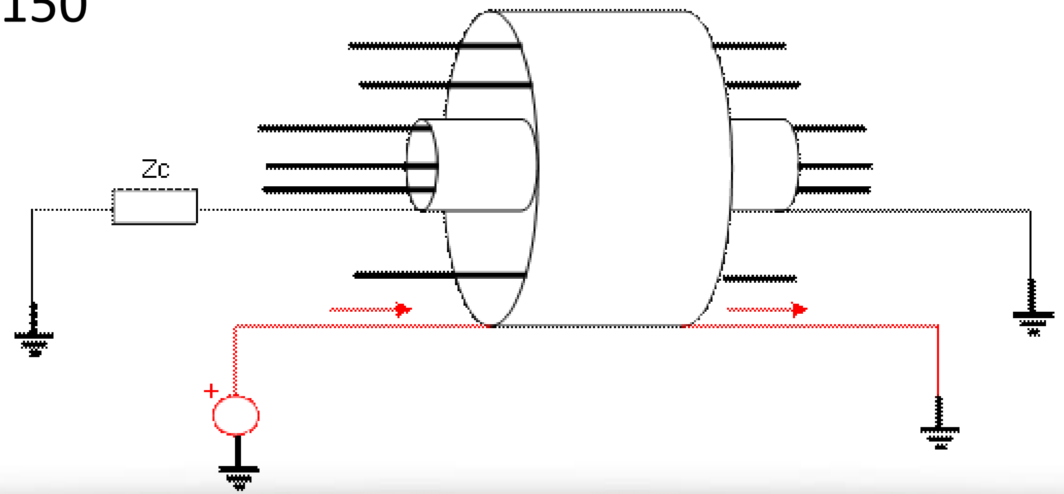
- The shield plays an important role in the attenuation of two types of noise.
  - Ground currents
  - External radiated fields
- The connection of internal & external shield has an impact on the noise distribution across the cable due to shield currents.
- The effect of these connections on the amount of noise coupled into the internal cables has been evaluated

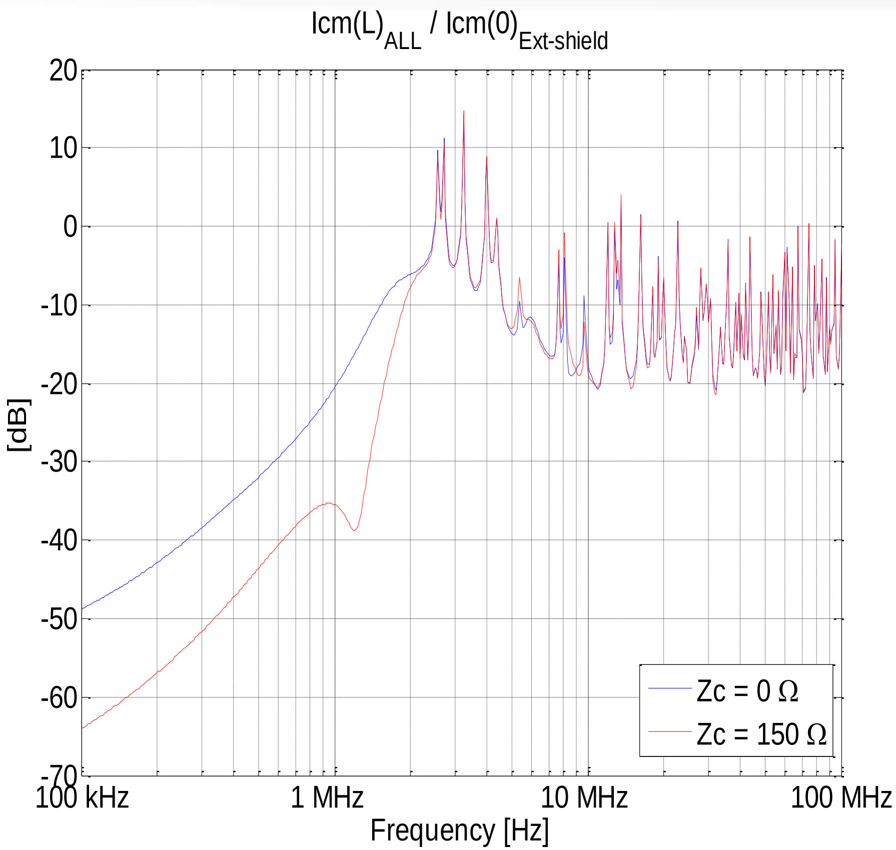
3.3 Noise propagation studies: Shield currents

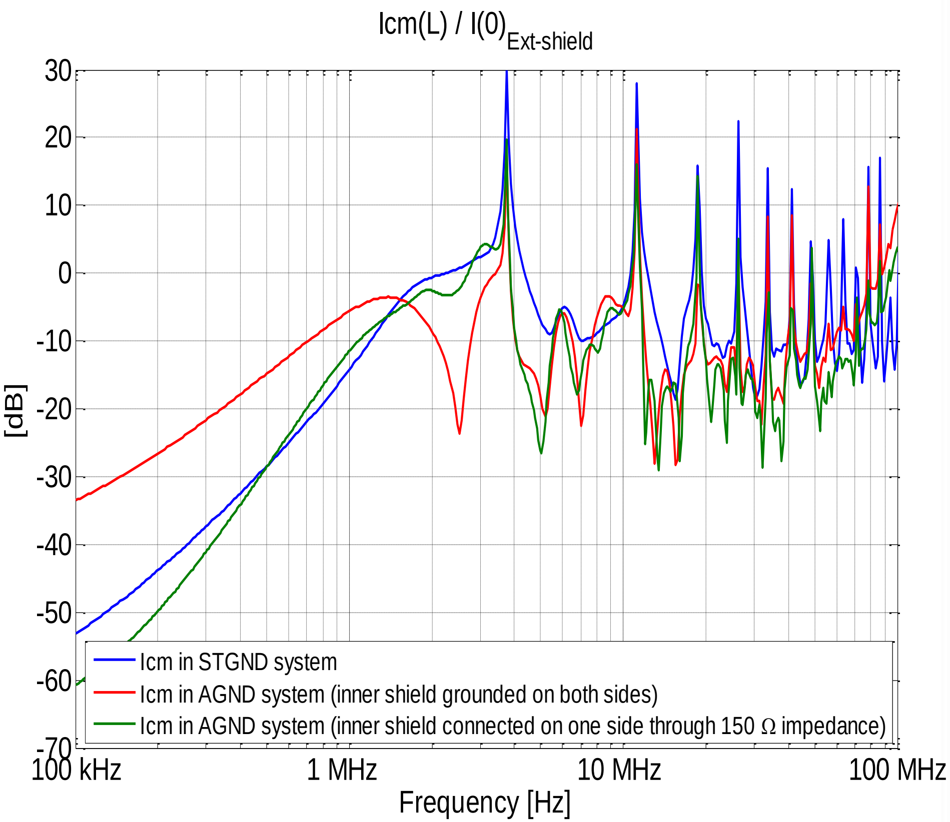
- **Ground currents -** Internal shield connection effects
  - Ground voltage is applied to the external shield
  - The noise couple to the cable is analyzed:
    - In the whole system
    - In each system (Analogue system / Steering system)
  - This noise distribution has been analyzed for several inner shield connections (Zc)
    - 0 & 150

Ish(0)



3.3 Noise propagation studies: Shield currents





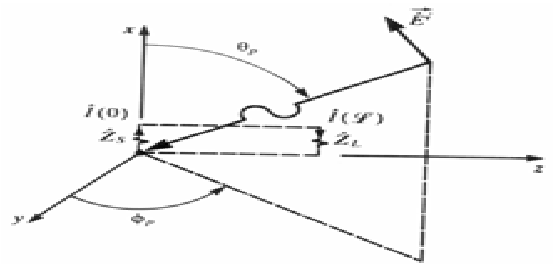
- The lower impedance connection of internal shield couples more noise into inner system (ANG system)

3.3 Noise propagation studies: Shield currents

- **Radiated field (Ambient noise)**- External shield connection
  - The cable is illumined by an external electromagnetic field is analyzed (1V/m) polarized to one direction.
- Two cases have been considered
  - External shield connected to both ends
  - No external shield
    - Similar case to shield not connected (some simplification)
- During this study the internal shield has been connected to both ends (**worst scenario**)

$$V_F(z)=2h\hat{E}_0\left[\frac{Sin(\beta_x h)}{\beta_x h}\right]e^{-j\beta_Z Z}(j\beta_z e_x - j\beta_x e_z)$$

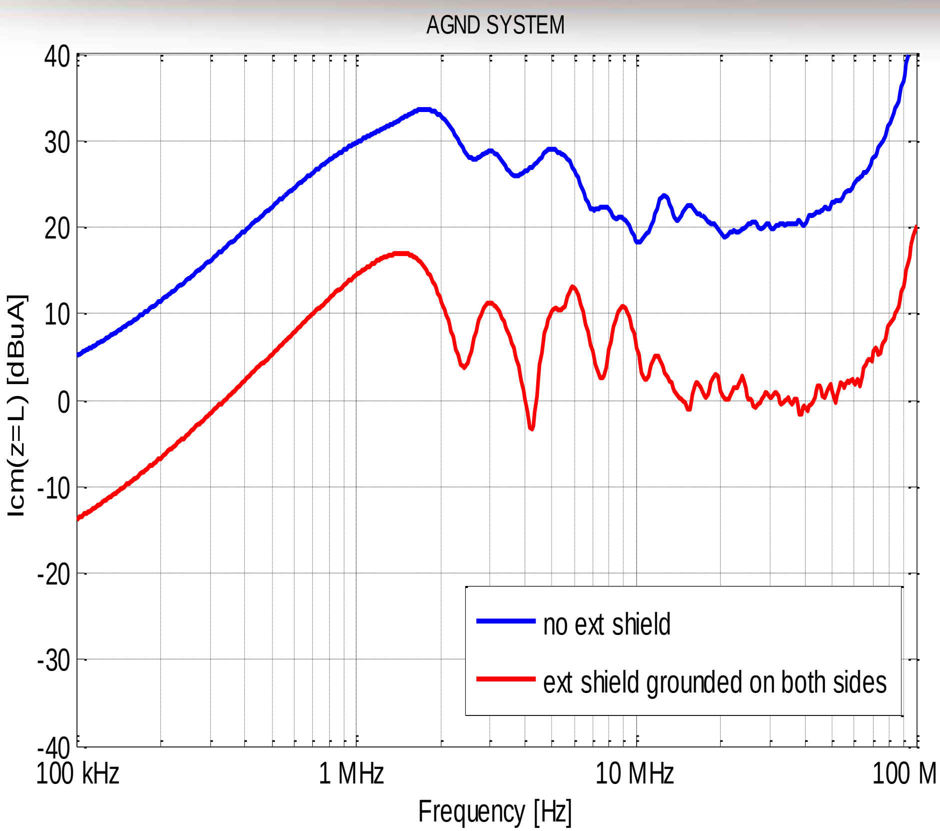
$$I_F(z)=-j2C.h.\ \hat{E}_0\left[\frac{Sin(\beta_x h)}{\beta_x h}\right]e^{-j\beta_Z Z}(e_x)$$

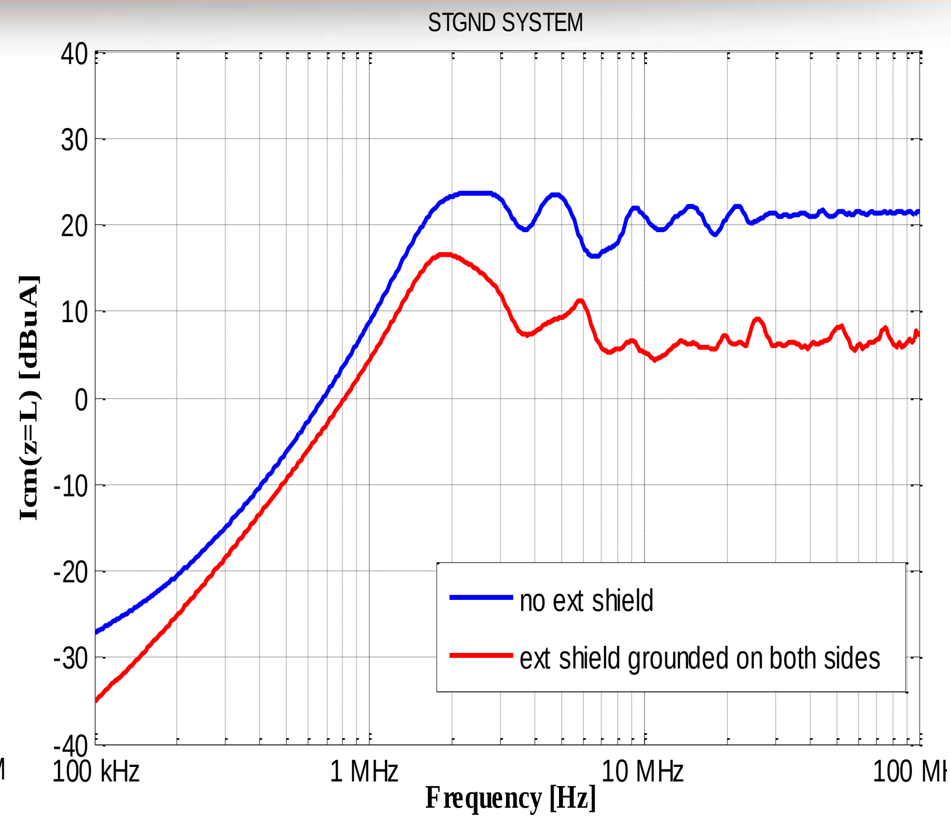


$$e_x=1, e_y=e_z=0$$

$$\beta=\omega\sqrt{\mu\varepsilon}$$

3.3 Noise propagation studies: Shield currents





- Shield connected to both ends improves the rejection to noise of cable.

4. CONCLUSIONS

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- The noise propagations issues of PXD power cable have been presented
  - The study has been carried out using MTL models
- This study has shown useful information for PXD integration aspects & shield connections coordination.
  - CM & DM noise levels are similar in cables with common power return
  - The noise coupled into sense lines or non-common neighboring system is smaller
  - No ground connection of internal shield seems to present a better performance of the cable against shield currents
  - The connection to ground (both sides) of the external shield is a good barrier to external fields .