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ITAINNOVA
INSTITUTO TECNOLÓGICO DE ARAGÓN

Noise propagation issues in complex power cables for HEP detectors

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OUTLINE

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- **2. Cable Model**
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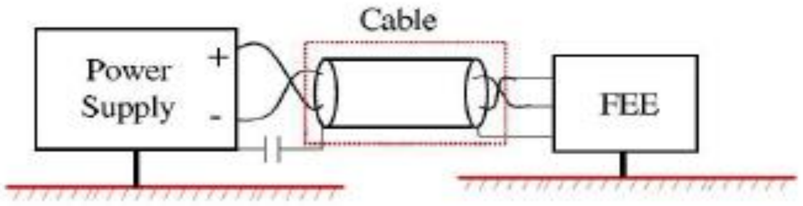
  - 3.3 Shield currents (Ground currents & Radiated noise)
- **4. Conclusions**

1. Introduction

*The main goal of a **EMC** based **design** approach for HEP **detectors** is to characterize the electromagnetic environment in order to **minimize noise emissions** and **maximize the immunity** of the **detector** system.*

- High Energy physics experiments are supplied by thousands of power supply units placed in **distant areas** from the front-end electronics.
- Power supply units and the FEE are connected through **long power cables than propagate the output noise from the power supplies to the detector**.
- These studies **address the effect of long cables on the noise propagation** and the impact that those cables have on the conducted emission levels required for the power supplies and the selection of EMI filters for the FEE low voltage input.



1. Introduction

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- The specific analysis that is going to be presented is part of the **EMC project for PXD (DEPFET Technology).**
- The project has been divided into four working packages
  - ✓ WP1: Grounding and shielding strategy for PXD
  - ✓ WP2: Conducted and Radiated Noise emissions test.
    - PS units & FEE
  - ✓ **WP3:Noise propagation issues in power cables**
  - – WP4:Immunity issues of PXD system.
- Main goal: EMISSIONS vs IMMUNITY--->MARGIN

*This methodology has been applied in **Belle II experiment** in order to define the electronic integration key parameters than minimize the noise level present inside the vertex volume composed by 2 different technologies: **SVD** (Double side silicon microstrip technology)+ **PXD** (DEPFET technology).*

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

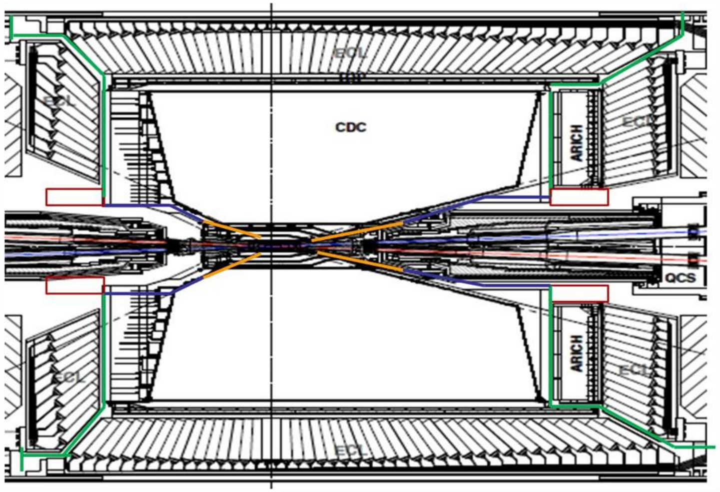
HEPHY Institute of High Energy Physics ÖAW

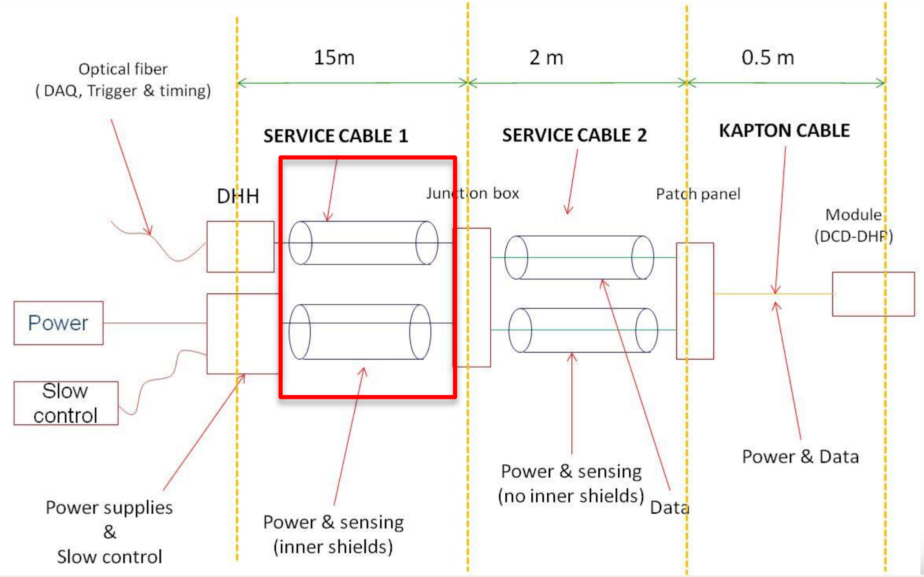
Belle II SVD

KEK HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

1. Introduction

- **The noise propagation studies has been focused on power cable 1**
  - It crosses all the experiment (15 meter long aprox.).
  - Low impedance connection to “external” world .
- **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.



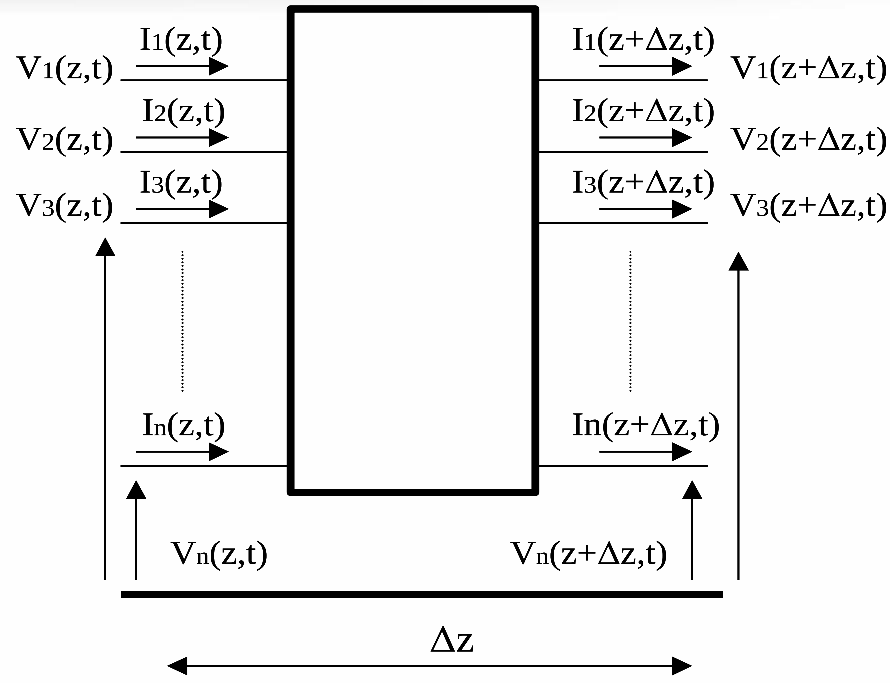


2. Cable Model

- The power cable is a very complex cable
- **Power , Bias & sense**
- Around 30 conductors
  - Internal & external shields
- Structure / STEER & ANALG
  - 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

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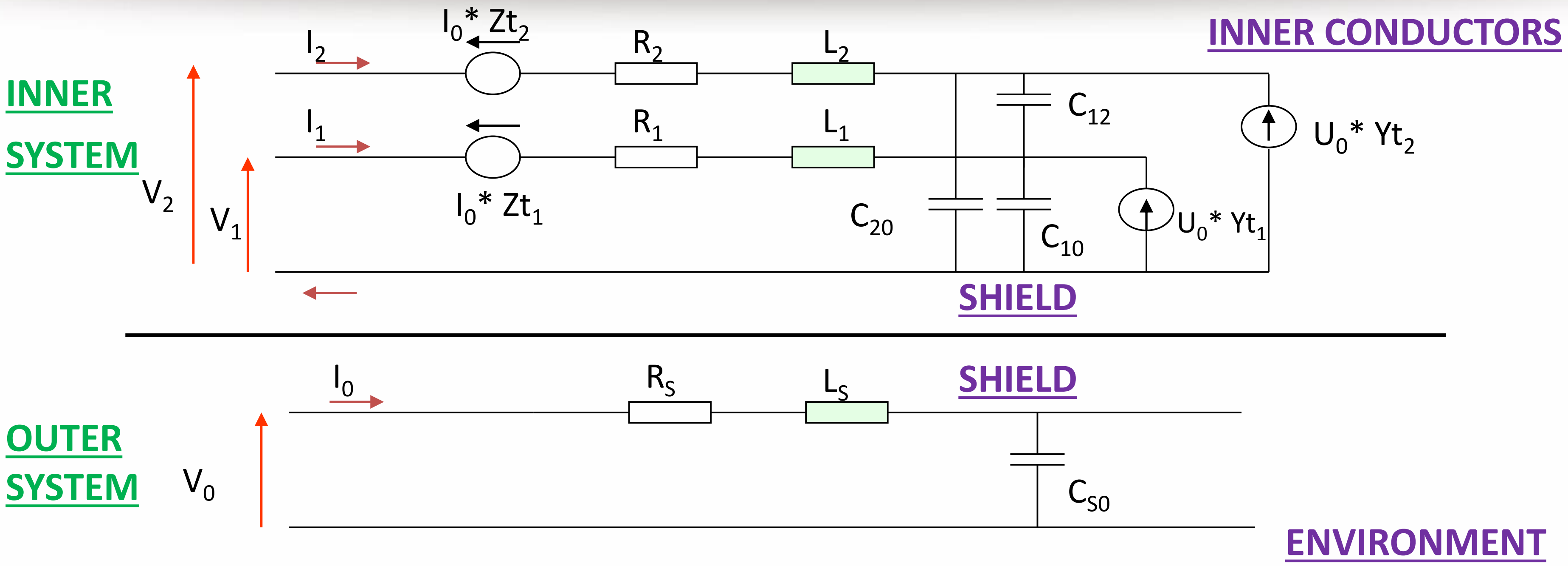

$$\frac{\partial}{\partial z}V(z,t) = -R\,I(z,t) - L\frac{\partial}{\partial t}I(z,t) + Zt \cdot Io(z,t)$$

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

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

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

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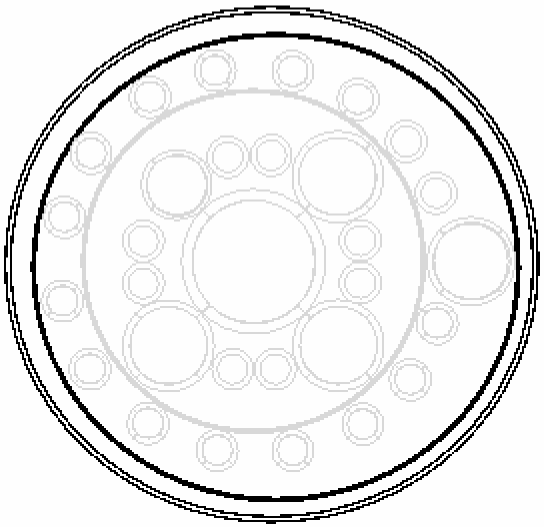
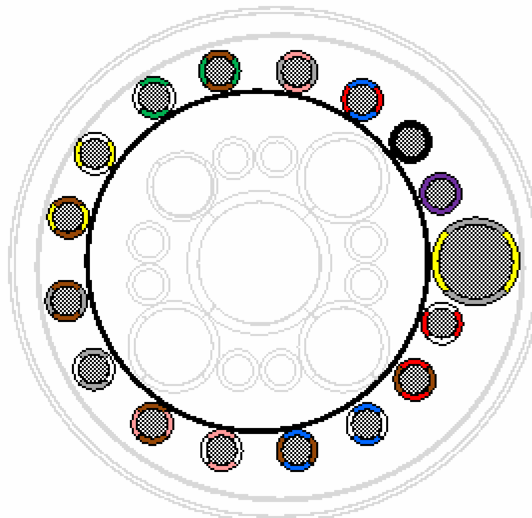
- The MTL model divided the cable into three systems



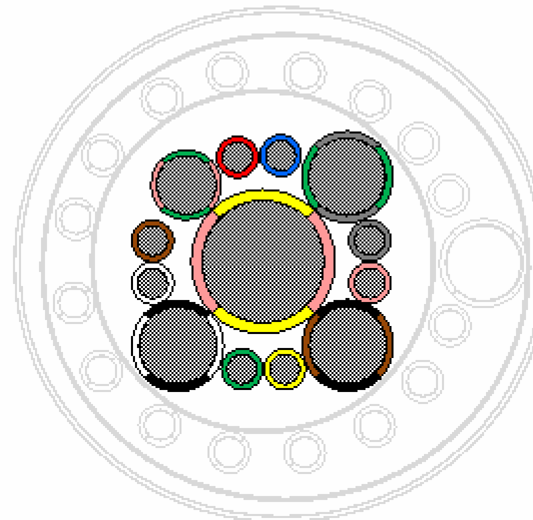
External system

Screen: copper
+
Aluminium foil



Steering system

17 conductors
+
Aluminium foil



Anlog/Dig system

13 conductors

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
1,8403E-08	8,4492E-09	1,4588E-08	1,5804E-08	1,3361E-08	1,1146E-08	1,3962E-08	1,5381E-08	2,055E-08	1,995E-08	3,1461E-07	5,349E-08	2,1868E-08	2,0123E-08	1,5523E-08	1,6119E-08	5,5114E-09	1,7006E-08
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
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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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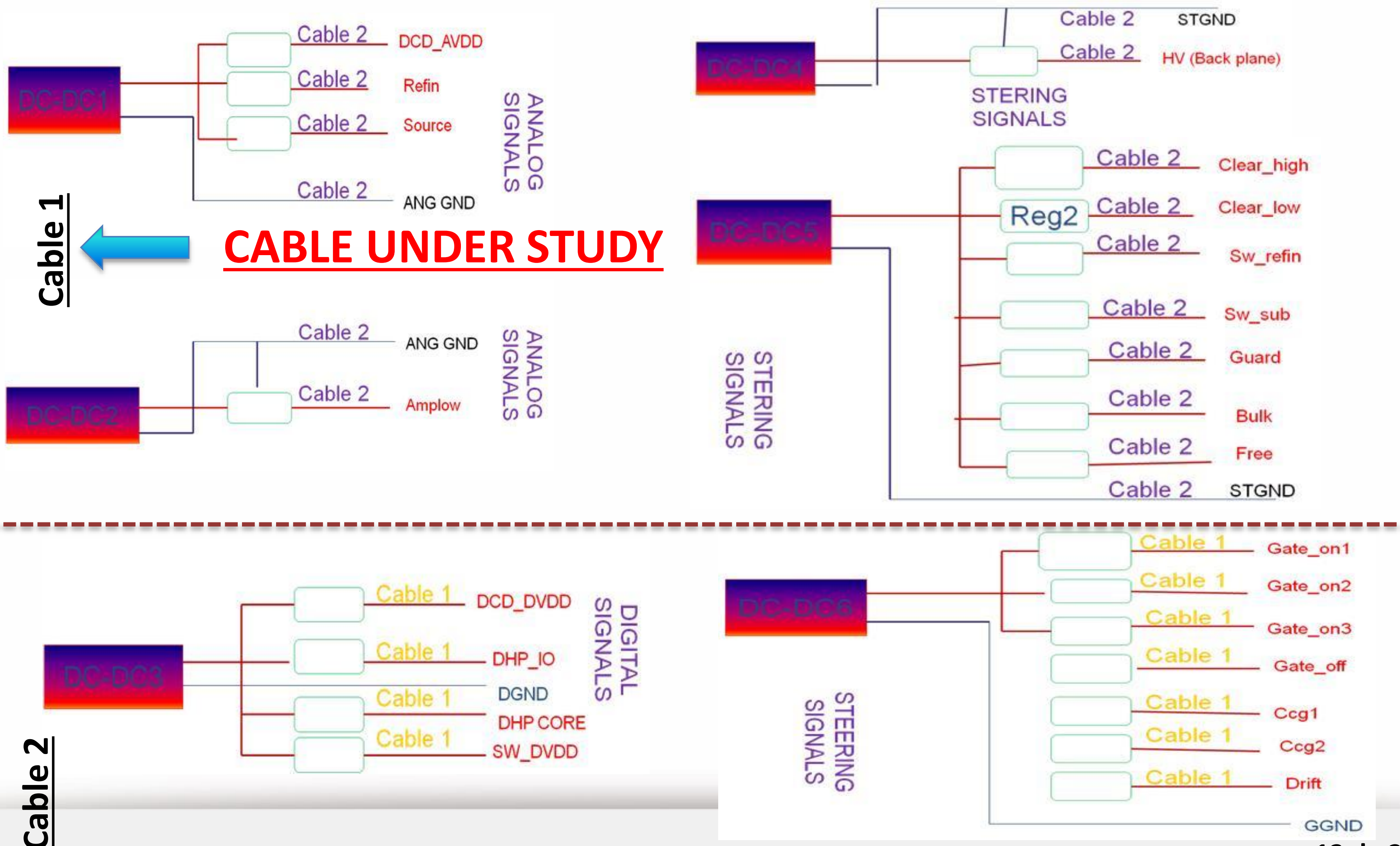
- **DEPFET power supply unit:**



3. Noise propagation studies

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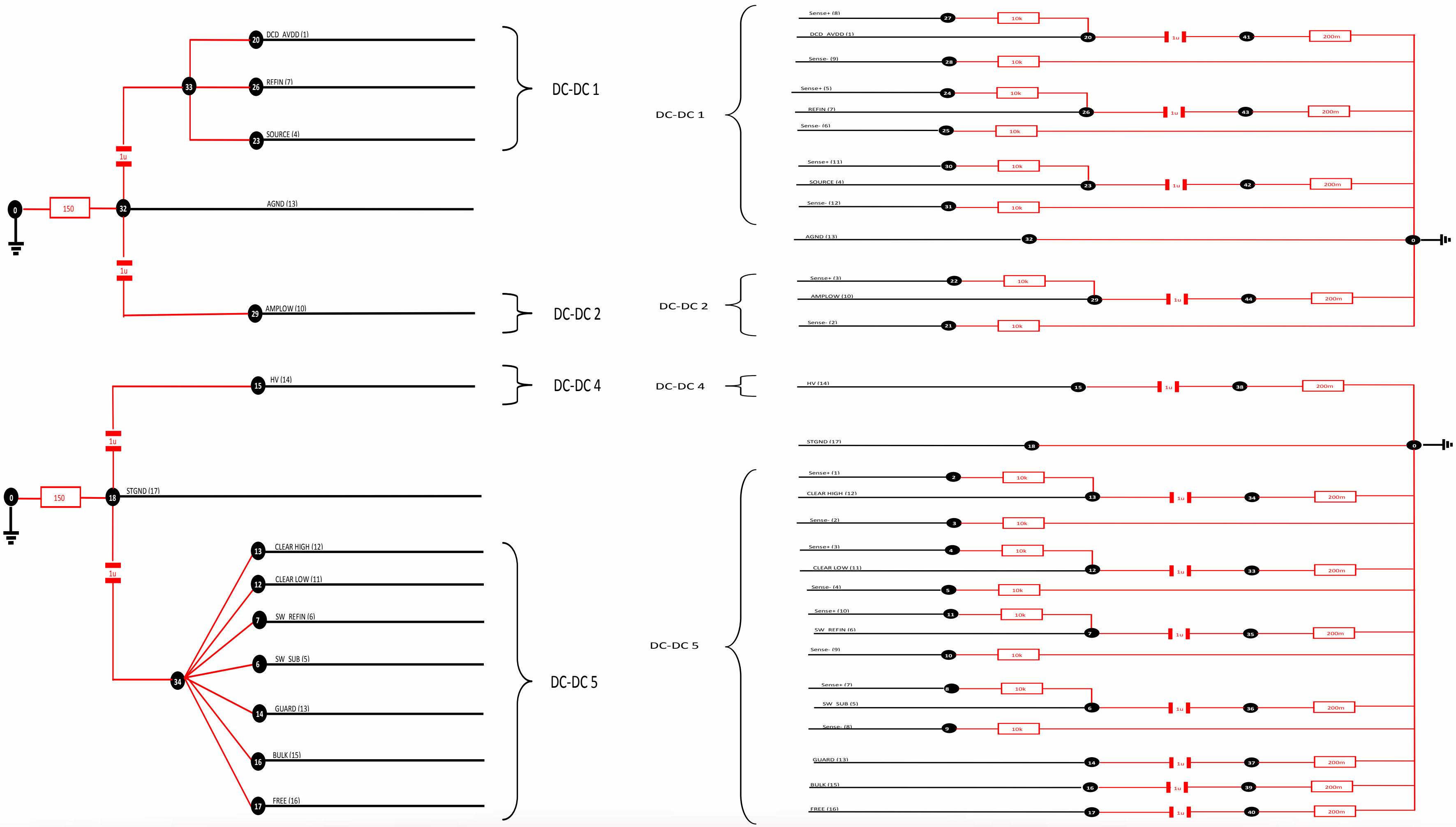
- **DEPFET PS and LOAD is complex.**

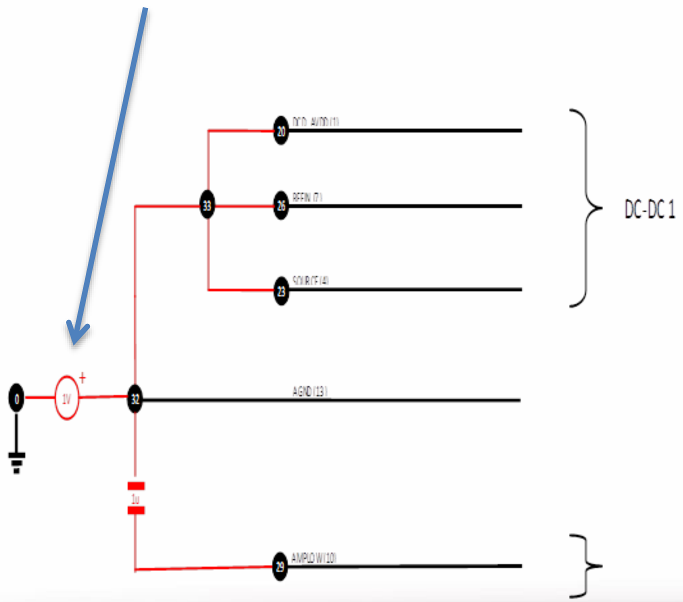


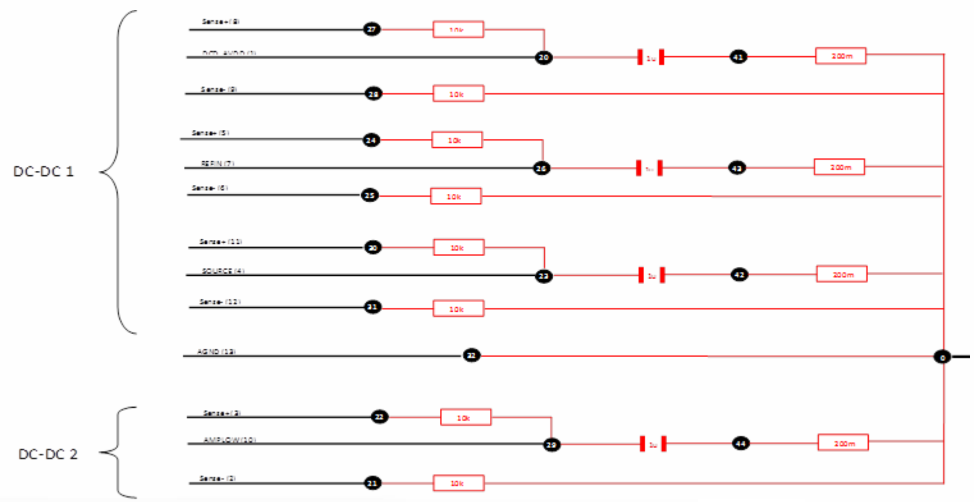
3.1 Noise propagation studies: CM noise from PS units

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

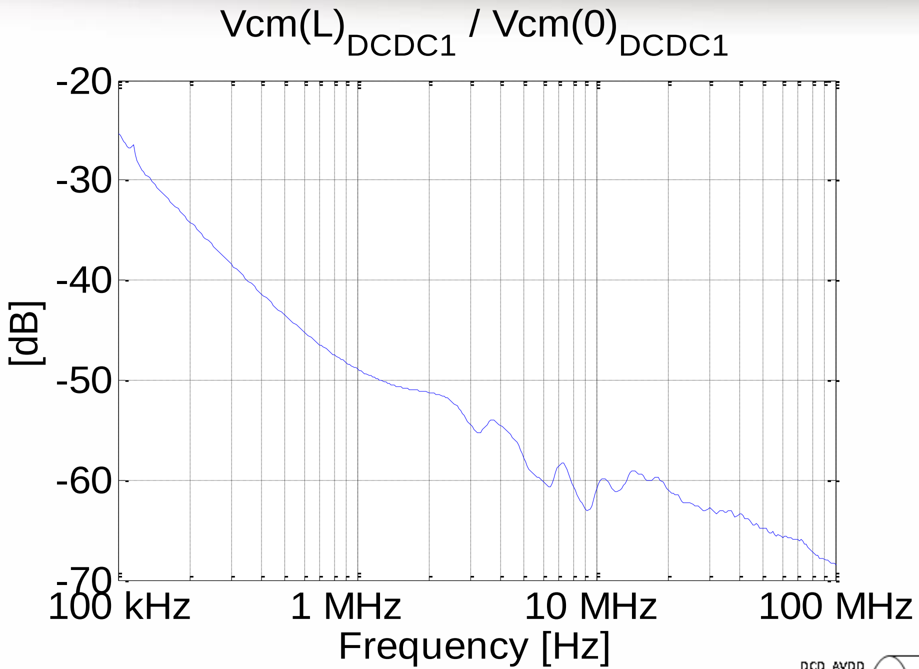
$$V_{cm-DC-DC1}(0)$$

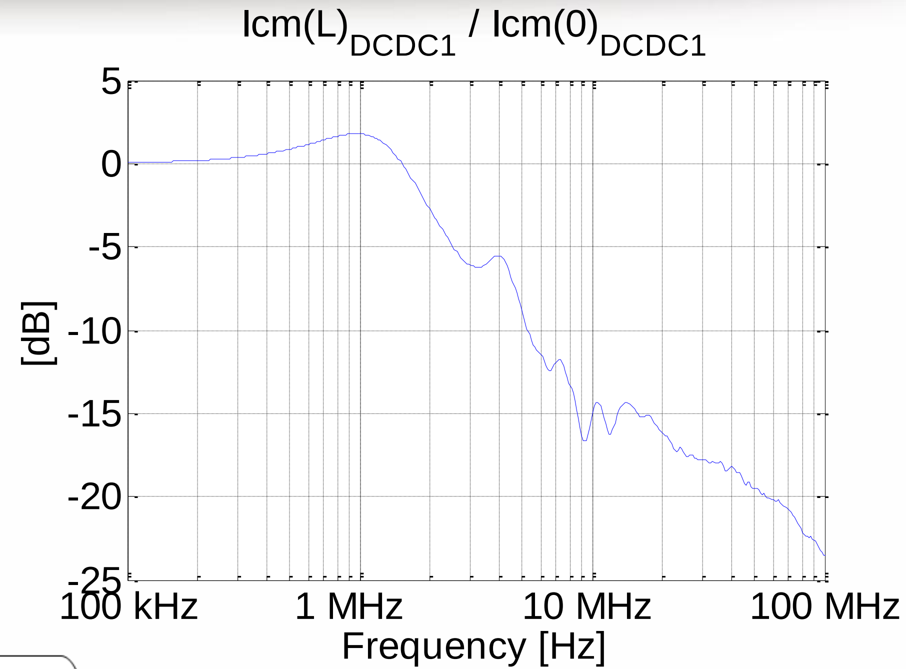
$$\hat{V}_{cm-DC-DC1}(L) = \frac{\sum_{n} \hat{V}_i(L)}{n} \qquad \hat{I}_{cm-DC-DC1}(L) = \frac{\sum_{n} \hat{I}_i(L)}{n}$$



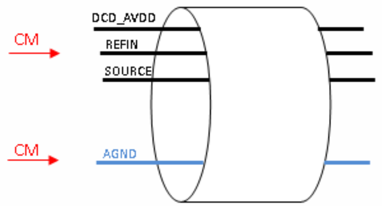


3.1 Noise propagation studies: CM noise from PS units





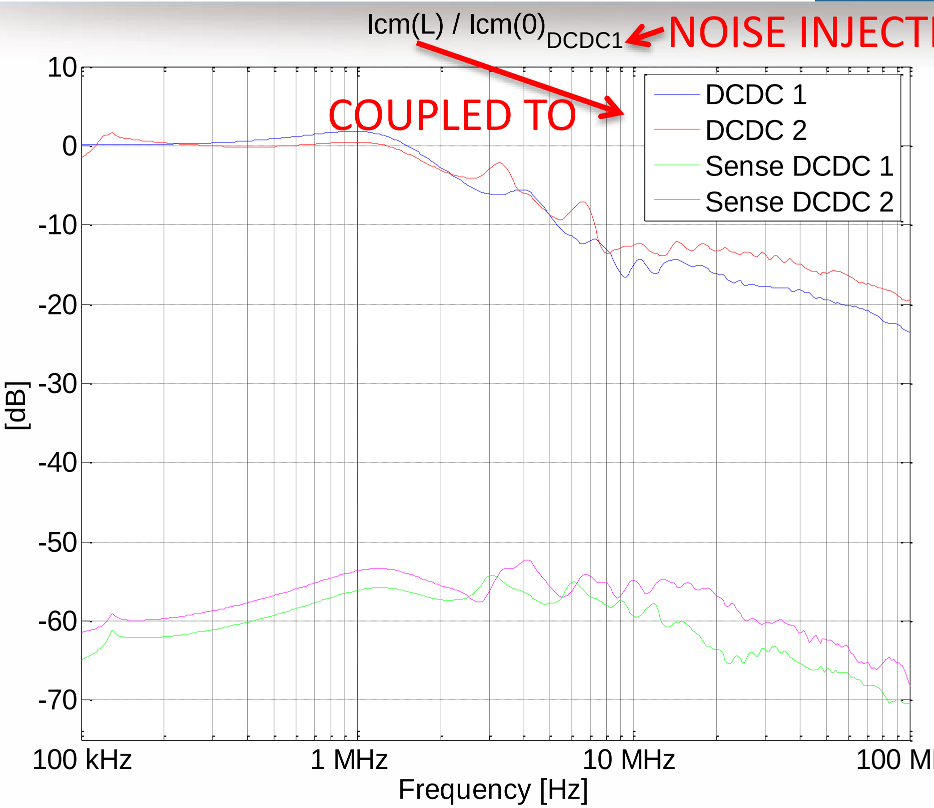
$$\hat{V}_{cm} = \frac{\hat{V}_{DCD\_AVDD} + \hat{V}_{REFIN} + \hat{V}_{SOURCE} + \hat{V}_{AGND}}{4}$$

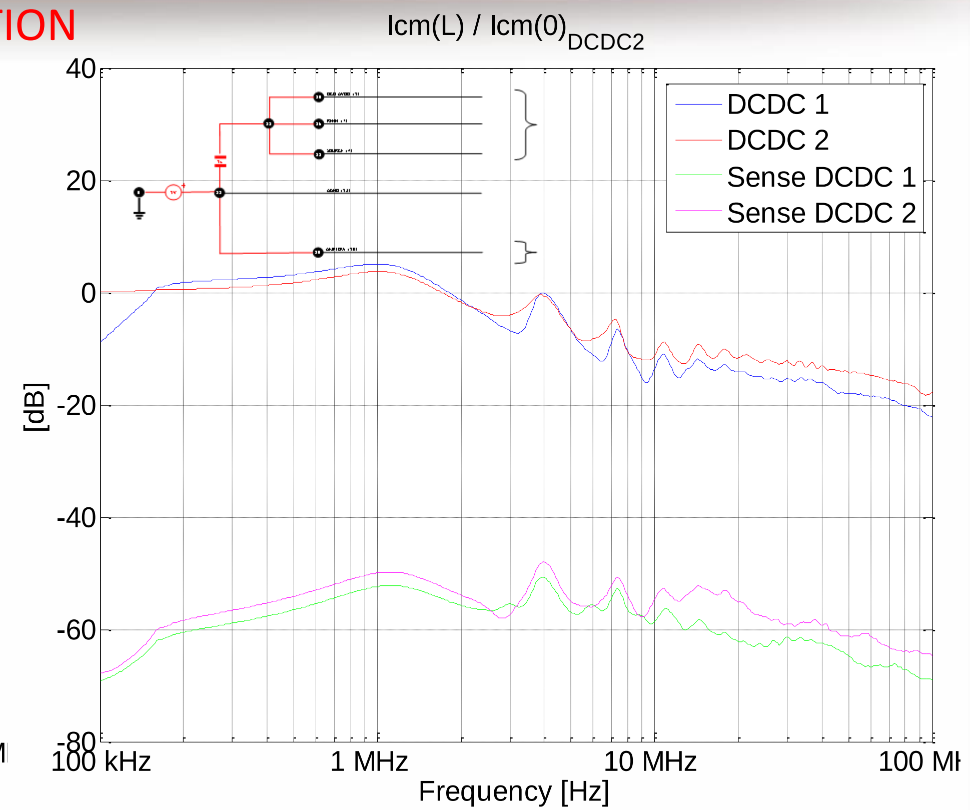


$$\hat{I}_{cm} = \frac{\hat{I}_{DCD\_AVDD} + \hat{I}_{REFIN} + \hat{I}_{SOURCE} + \hat{I}_{AGND}}{4}$$

- **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)**

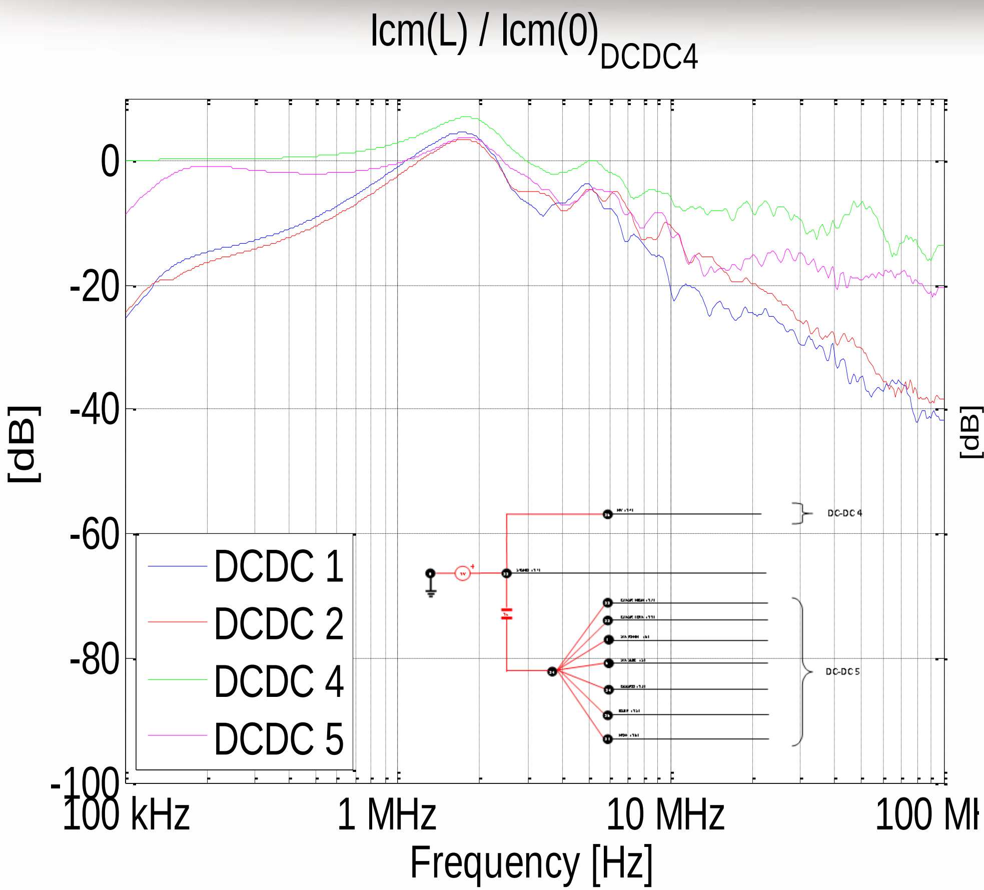
3.1 Noise propagation studies: CM noise from PS units

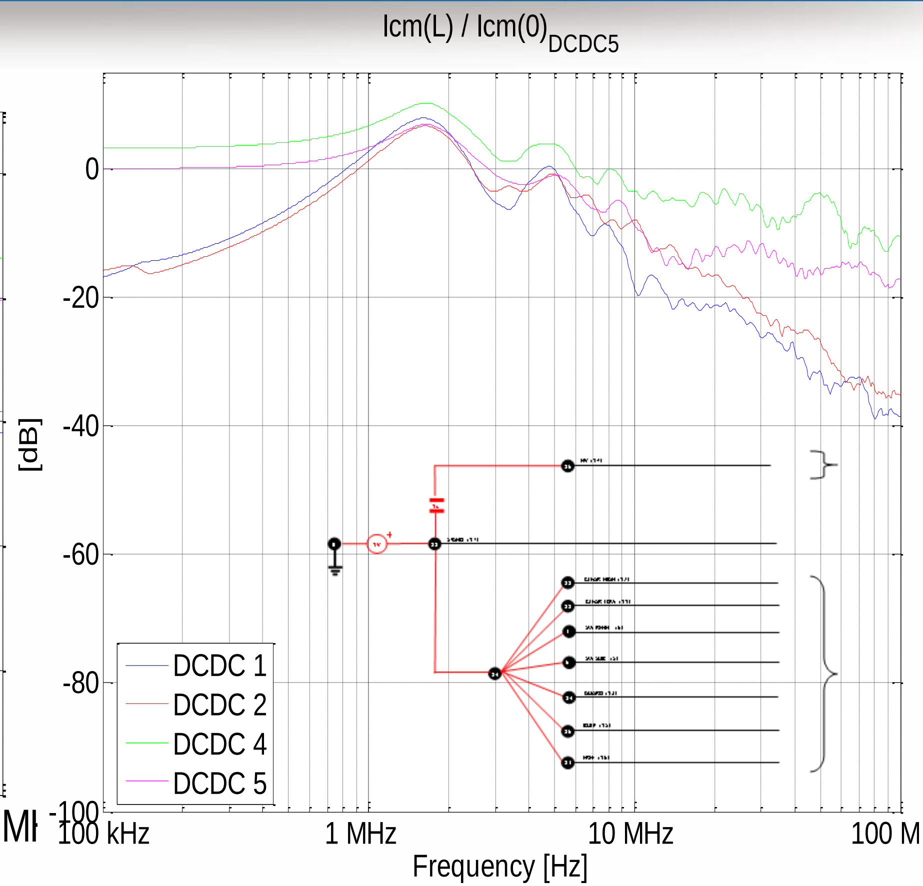




- **Low noise coupling to sense lines**
  - Due to the high impedance
- **Similar coupling from DCDC1 to DC-DC2 /DC-DC2 to DC-DC1**
  - Noise is defined by the common power return

3.1 Noise propagation studies: CM noise from PS units





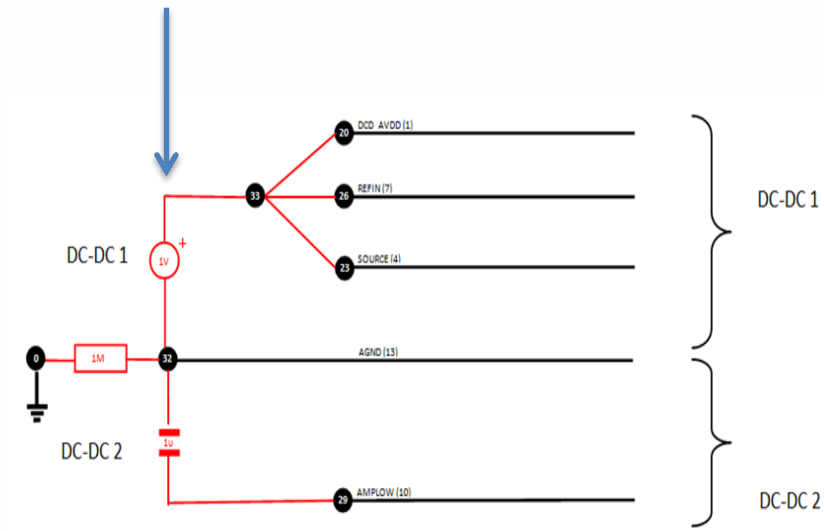
- **Similar coupling from DCDC4 to DC-DC5 or DC-DC5 to DC-DC4**
  - Noise is defined by the common power return
- **Lower coupling level to cable connected to other DC-DC/f(freq)**

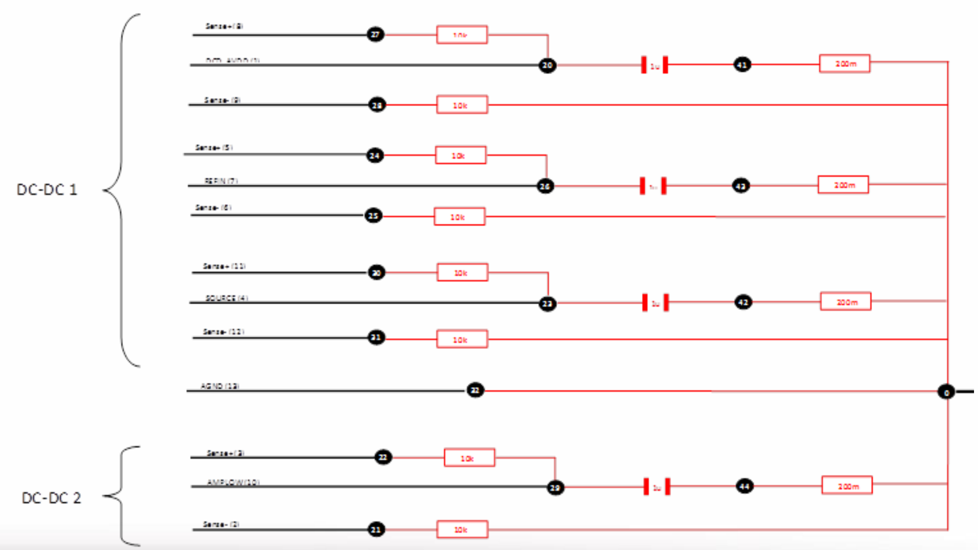
3.2 Noise propagation studies: DM noise from PS units (ripple)

- 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

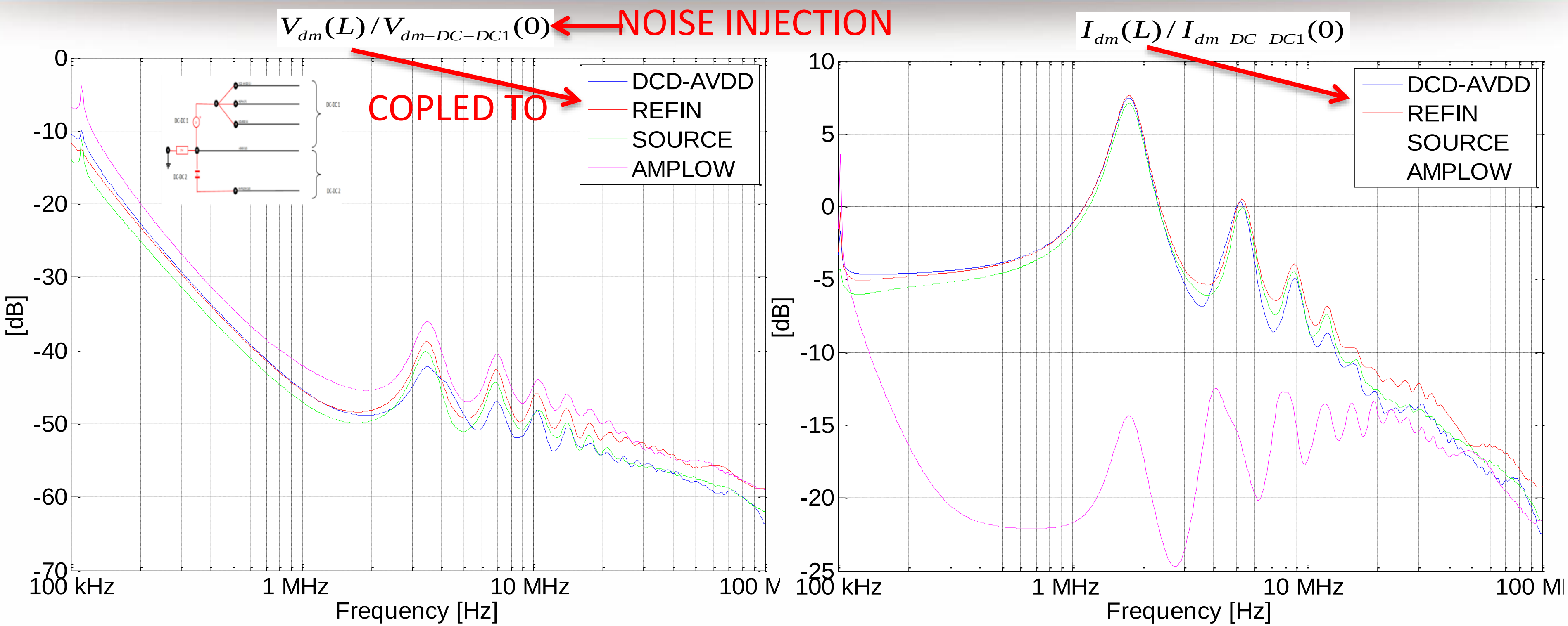
$V_{dm-DC-DC1}(0)$

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



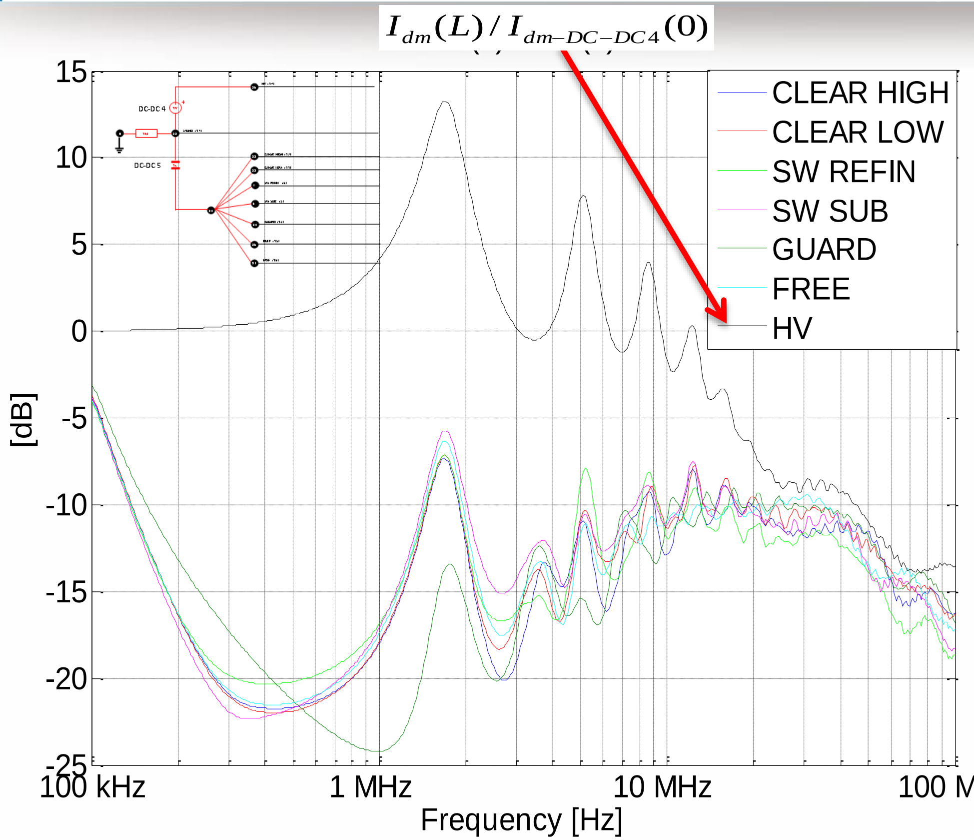


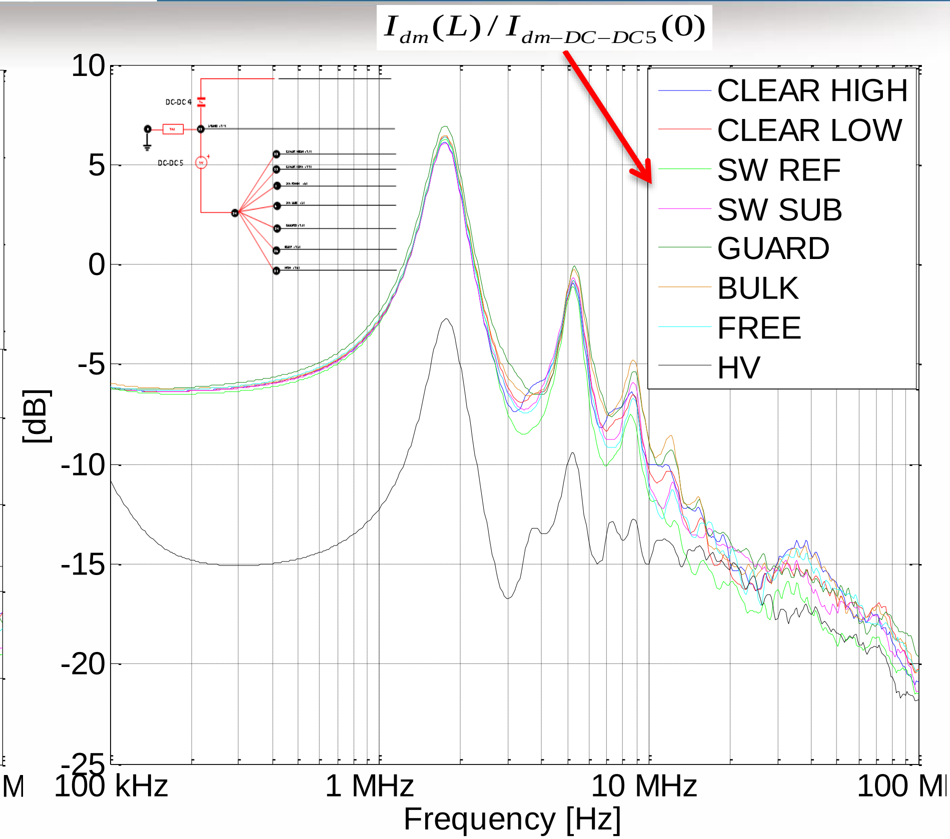
3.2 Noise propagation studies: DM noise from PS units (ripple)



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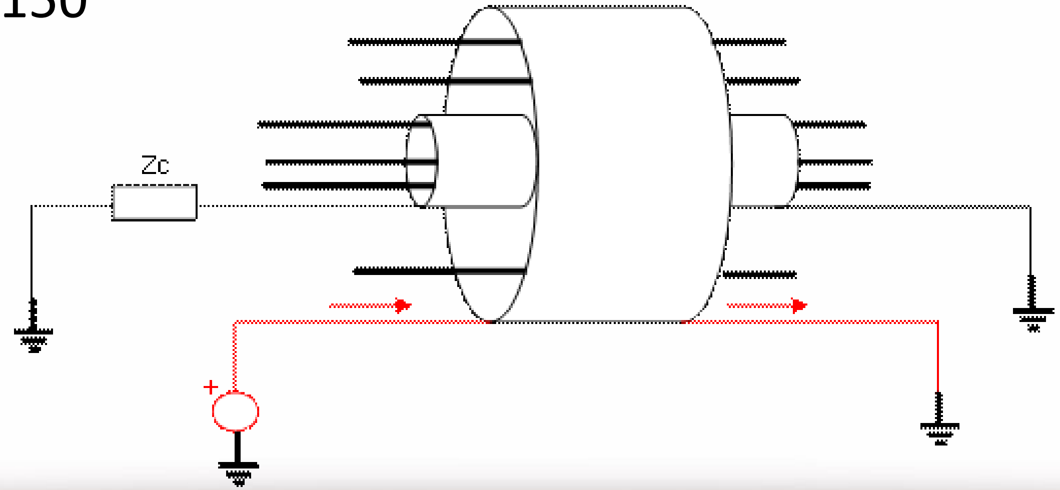
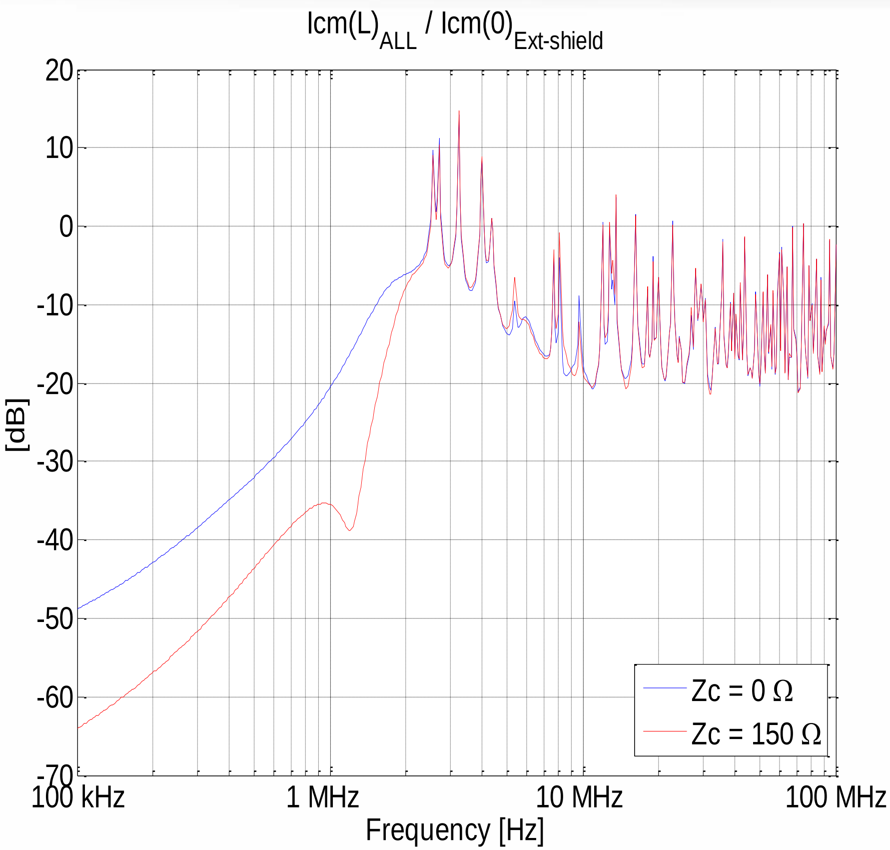
- The **shield** plays an important role in the **attenuation** of two types of noise.
  - **Ground currents**
  - **External radiated fields**
- The **connection** of internal & external shield has an **impact on the noise distribution** across the cable due to shield currents.
- **The effect** of these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

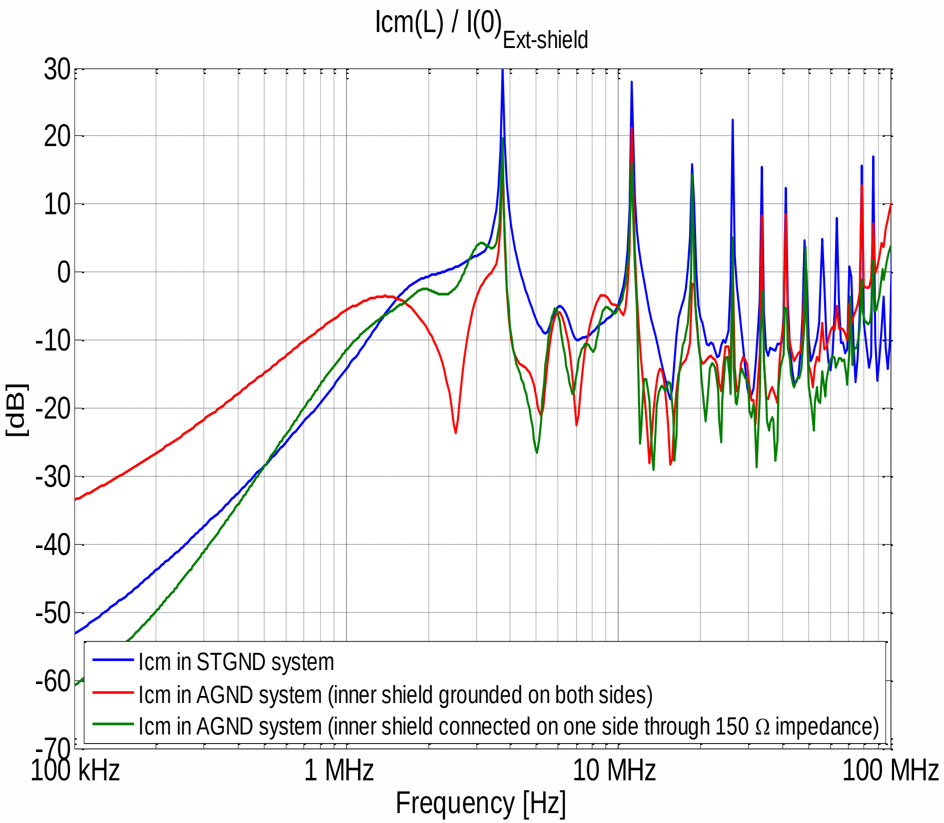
- **Ground currents -** Internal shield connection effects
  - Ground voltage is applied to the external shield
  - The noise coupled to the cable is analyzed:
    - In the whole system
    - In each system (Analogue system / Steering system)
  - This noise distribution has been analyzed for several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

Ish(0)



3.3 Noise propagation studies: Shield currents (ground currents)





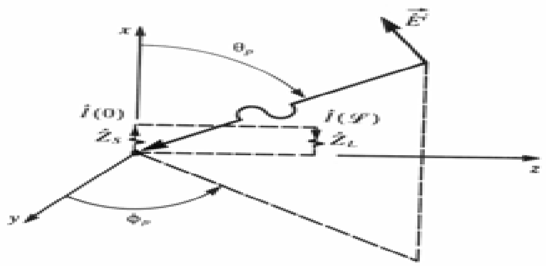
- The lower impedance connection of internal shield couples more noise into inner system (ANG system)

3.3 Noise propagation studies: Shield currents (External radiated noise)

- **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**)

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

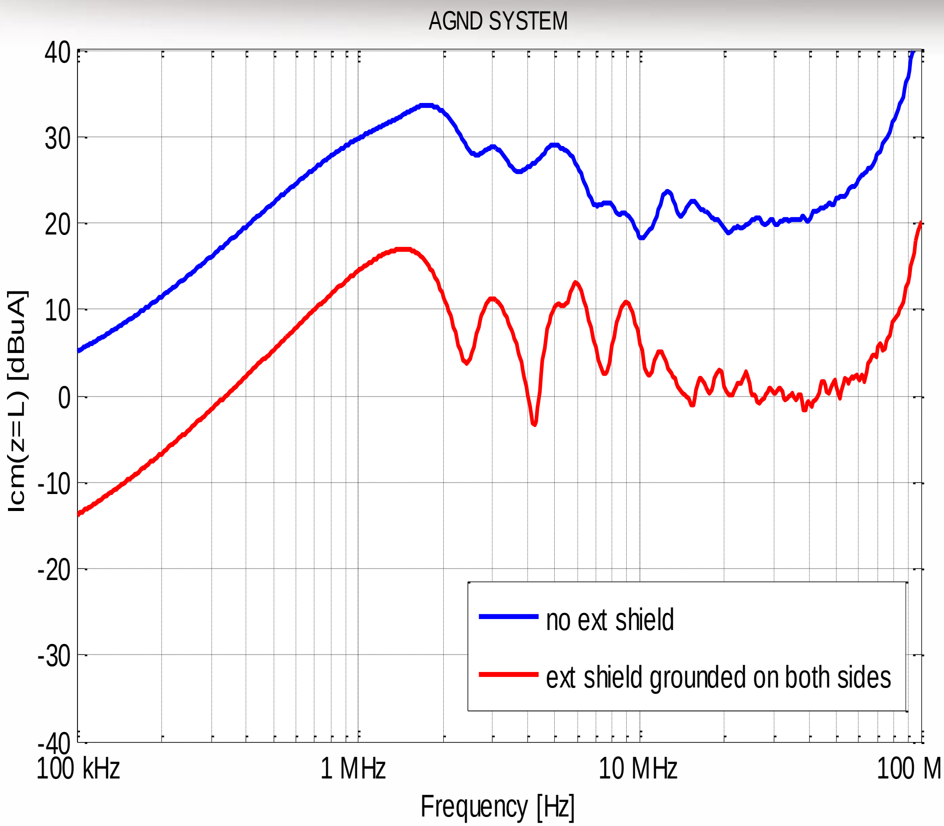
$$I_F(z) = -\,j\,2C.h.\;\hat{E}_0 \left[\frac{Sin(\beta_x\, h)}{\beta_x\, h}\right] e^{-j\beta_Z Z}\left(e_x\right)$$

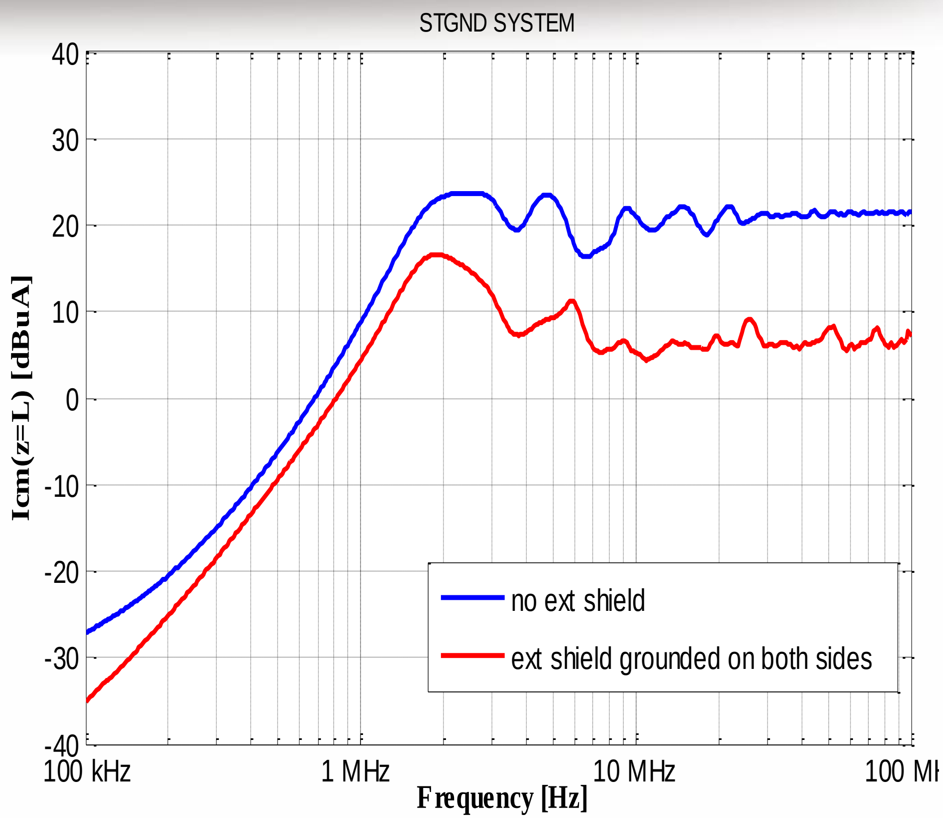


$$e_x = 1, e_y = e_z = 0$$

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

3.3 Noise propagation studies: Shield currents (External radiated noise)





- 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.

BACKUP SLIDES

2.1 Cable Model: Parameters

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Uncertainties

Phase 2

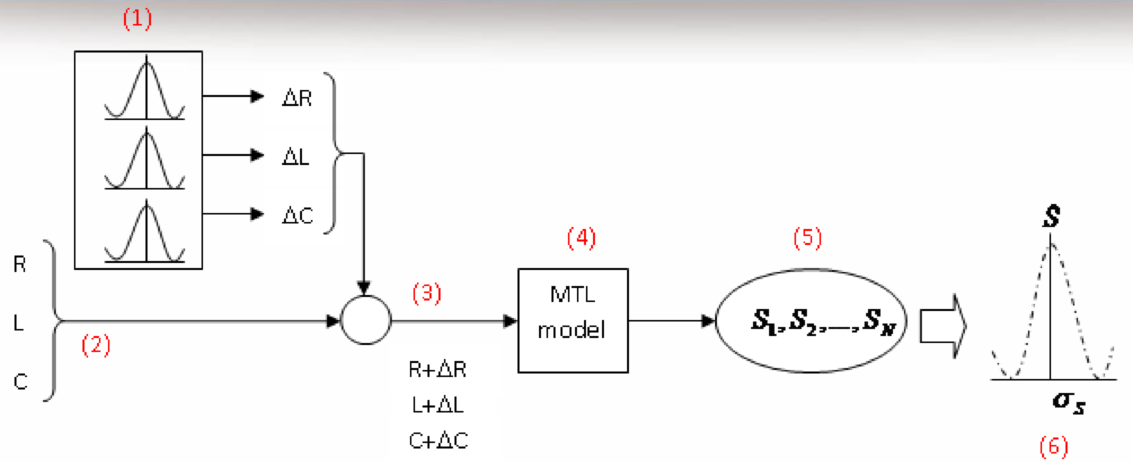

Figure: Simulation procedure including Montecarlo approach

σ Lij (H/m)														
	5,3275E-09	4,7452E-09	4,6574E-09	4,751E-09	4,6495E-09	4,6278E-09	4,7802E-09	4,6225E-09	4,6412E-09	4,6775E-09	4,7081E-09	4,8472E-09	4,7356E-09	4,6935E-09
	4,7452E-09	5,6852E-09	4,8592E-09	4,777E-09	4,8279E-09	4,8517E-09	5,0613E-09	4,7606E-09	4,8761E-09	4,6908E-09	4,8234E-09	4,875E-09	4,8574E-09	4,8215E-09
	4,6574E-09	4,8592E-09	5,5563E-09	4,7953E-09	4,7566E-09	4,7604E-09	5,0008E-09	4,6097E-09	4,7314E-09	4,6229E-09	4,9094E-09	4,8016E-09	4,9049E-09	4,7547E-09
	4,751E-09	4,777E-09	4,7953E-09	5,4507E-09	4,5982E-09	4,7999E-09	4,8322E-09	4,8211E-09	4,7175E-09	4,8419E-09	4,8932E-09	4,6422E-09	4,8952E-09	4,6848E-09
	4,6495E-09	4,8279E-09	4,7566E-09	4,5982E-09	5,5868E-09	4,8121E-09	4,8059E-09	4,8363E-09	4,8373E-09	4,6566E-09	4,5411E-09	4,5199E-09	4,8772E-09	4,8771E-09
	4,6278E-09	4,8517E-09	4,7604E-09	4,7999E-09	4,8121E-09	5,5501E-09	4,665E-09	4,8109E-09	4,7516E-09	4,8184E-09	4,8609E-09	4,8592E-09	4,8316E-09	4,8429E-09
	4,7802E-09	5,0613E-09	5,0008E-09	4,8322E-09	4,8059E-09	4,665E-09	5,5995E-09	4,7292E-09	4,9292E-09	4,6432E-09	4,9416E-09	4,7584E-09	4,7629E-09	5,0478E-09
	4,6225E-09	4,7606E-09	4,6097E-09	4,8211E-09	4,8363E-09	4,8109E-09	4,7292E-09	5,3243E-09	4,8487E-09	4,774E-09	4,7217E-09	4,5344E-09	4,9549E-09	4,6521E-09
	4,6412E-09	4,8761E-09	4,7314E-09	4,7175E-09	4,8373E-09	4,7516E-09	4,9292E-09	4,8487E-09	5,4986E-09	4,8049E-09	4,9467E-09	4,808E-09	4,7528E-09	4,882E-09
	4,6775E-09	4,6908E-09	4,6229E-09	4,8419E-09	4,6566E-09	4,8184E-09	4,6432E-09	4,774E-09	4,8049E-09	5,3881E-09	4,6834E-09	4,8622E-09	4,6814E-09	4,6677E-09
	4,7081E-09	4,8234E-09	4,9094E-09	4,8932E-09	4,5411E-09	4,8609E-09	4,9416E-09	4,7217E-09	4,9467E-09	4,6834E-09	5,4696E-09	4,8646E-09	4,773E-09	4,8103E-09
	4,8472E-09	4,875E-09	4,8016E-09	4,6422E-09	4,5199E-09	4,8592E-09	4,7584E-09	4,5344E-09	4,808E-09	4,8622E-09	4,8646E-09	5,6349E-09	4,8113E-09	4,881E-09
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	4,6935E-09	4,8215E-09	4,7547E-09	4,6848E-09	4,8771E-09	4,8429E-09	5,0478E-09	4,6521E-09	4,882E-09	4,6677E-09	4,8103E-09	4,881E-09	4,9273E-09	5,4437E-09
	4,7853E-09	5,0083E-09	4,8314E-09	4,8003E-09	4,9663E-09	4,7119E-09	4,8874E-09	4,742E-09	4,7992E-09	4,6708E-09	4,8966E-09	4,779E-09	4,839E-09	4,9324E-09
	4,6098E-09	4,6649E-09	4,6985E-09	4,8527E-09	4,8571E-09	4,6662E-09	4,7142E-09	4,6179E-09	4,7265E-09	4,6488E-09	4,665E-09	4,6399E-09	4,6919E-09	4,7319E-09
	4,7535E-09	4,8491E-09	4,8561E-09	4,7299E-09	4,8483E-09	4,9106E-09	4,7472E-09	4,7368E-09	4,6221E-09	4,9359E-09	4,7819E-09	4,9121E-09	5,0013E-09	4,6974E-09
	4,8984E-09	4,8892E-09	4,7055E-09	4,7191E-09	4,789E-09	4,8689E-09	4,836E-09	4,6902E-09	4,7162E-09	4,6484E-09	4,5877E-09	4,7981E-09	4,8103E-09	4,842E-09

(1) Uncertainty of each measured matrix.

(2) R, L ,C: measured values

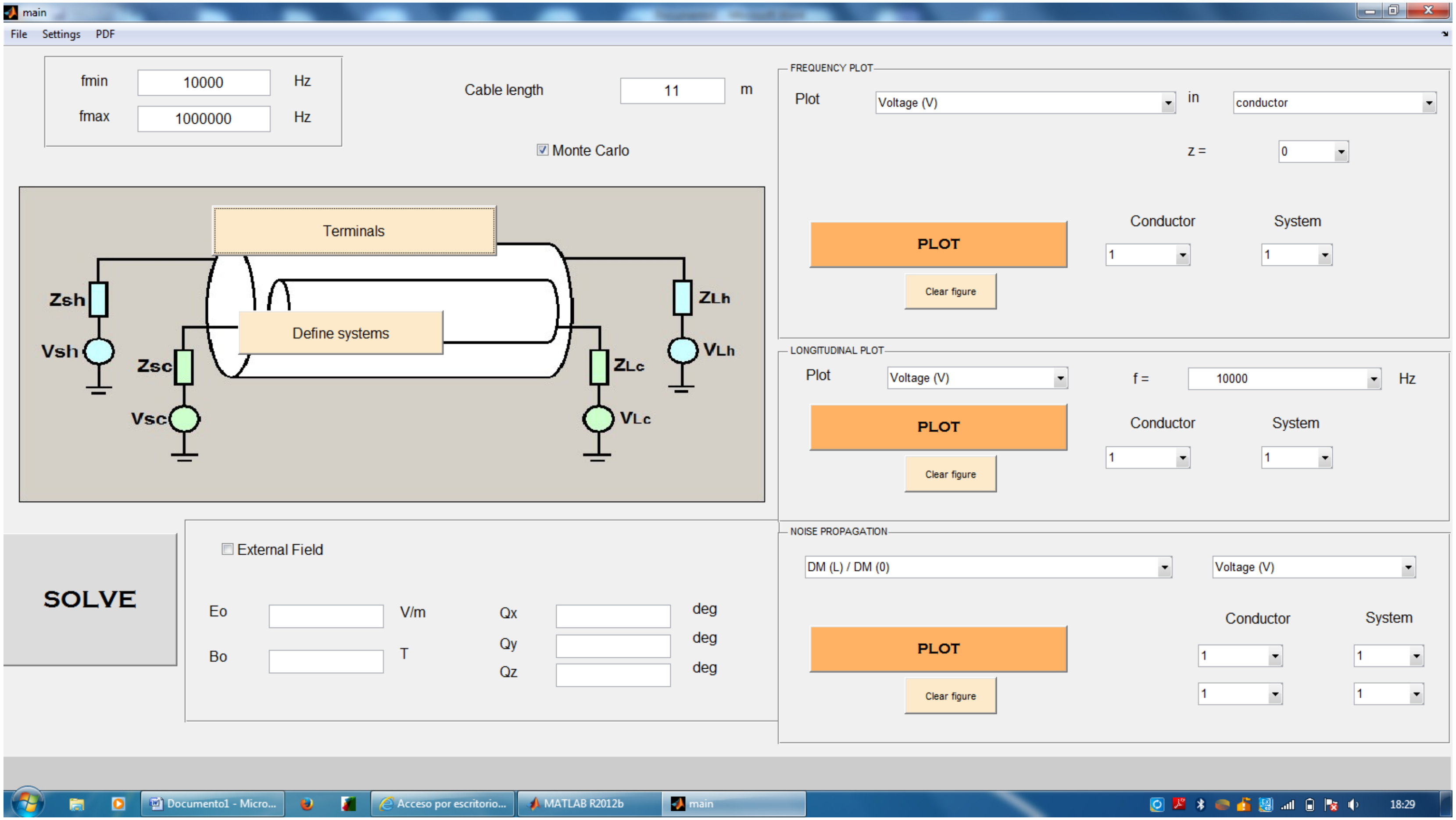
(3) New values for R,L,C used in the MTL model

(4) MTL model

(5) Computed solutions (N times=number of samples)

(6) Result: N solutions (S=average value with deviation) represent the probability distribution of the final solution, including the variation in the measured values (cable position), tolerances, testing setup, measuring uncertainty.

2. Cable Model: MTL



2. Cable Model: Validation

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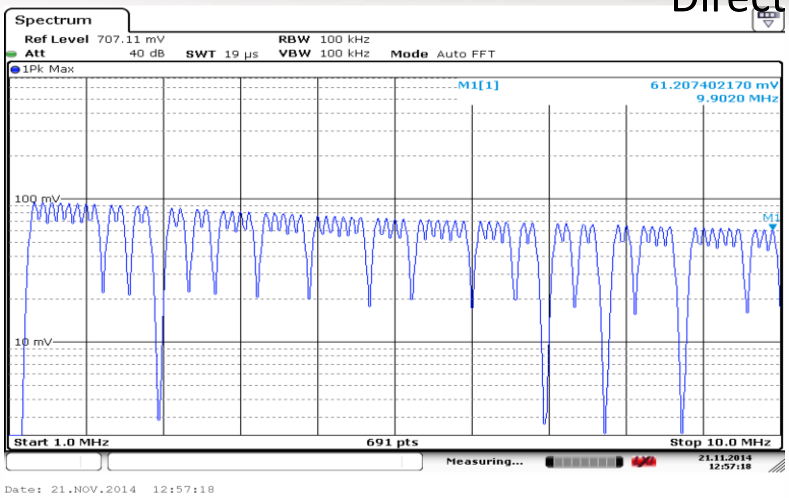
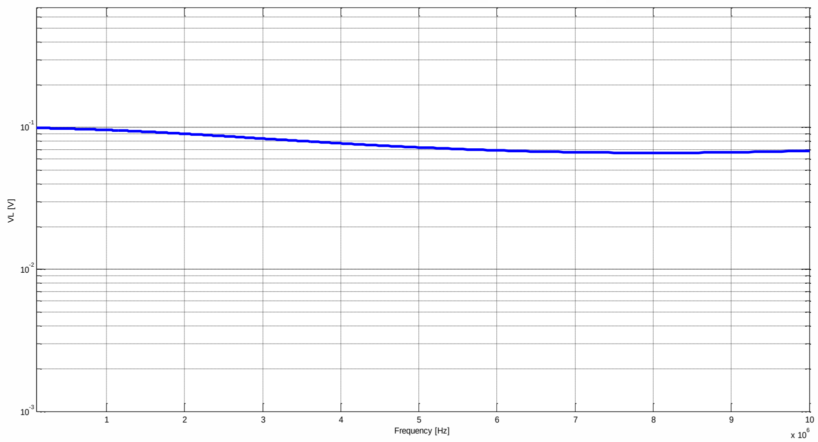
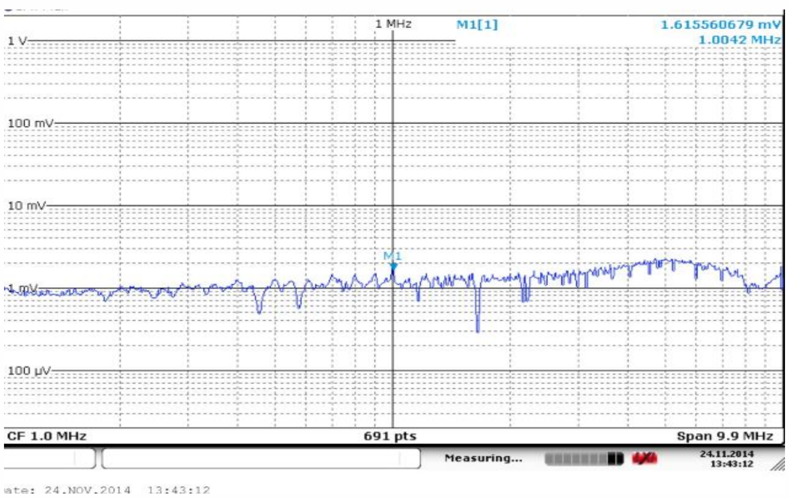
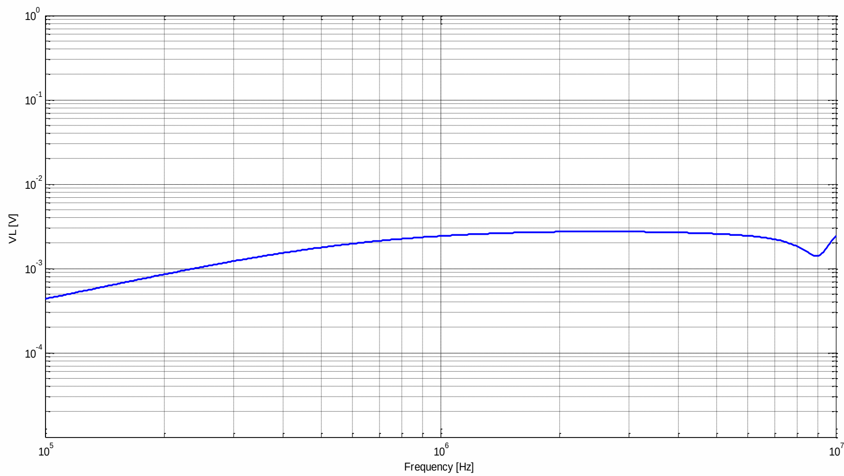
Direct coupling









Indirect coupling