Impact of Current-Compensated Choke Design on EMI Filter Performance

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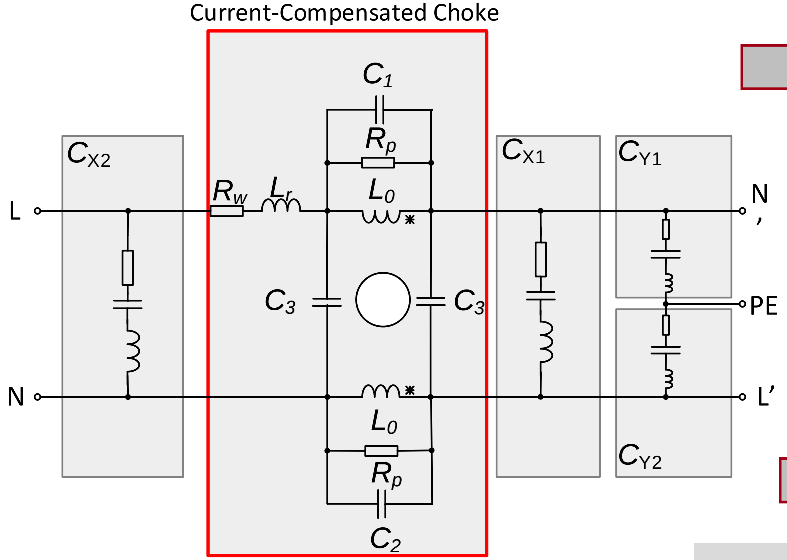
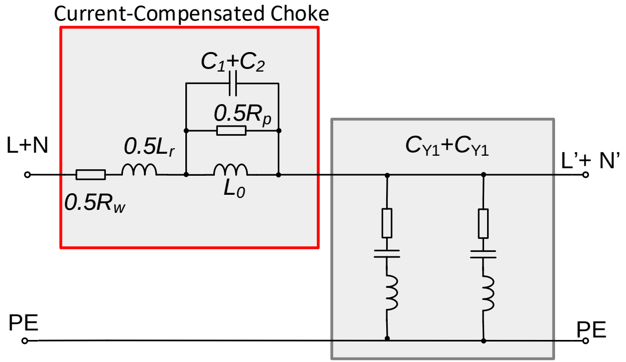
Goal of Presentation

- Current-compensated choke in EMI filter
- Comparison of different current-compensated choke designs concepts
- Parameters impact on current-compensated choke properties
- Comparison of core shapes
- Magnetic material impact on current-compensated choke properties:
  - Comparison of ferrite cores with different permeability
  - Comparison of nanocrystalline cores with different permeability
  - Comparison of nanocrystalline vs. ferrite cores
  - Comparison of nanocrystalline and ferrite saturation properties
- Impact of winding method on current-compensated choke properties
- Conclusion

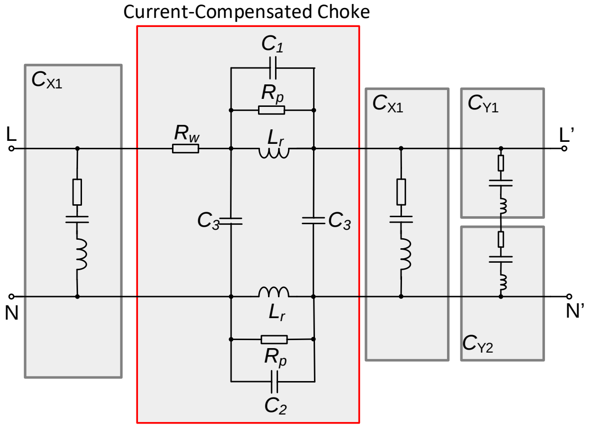
HF Model EMI Filter



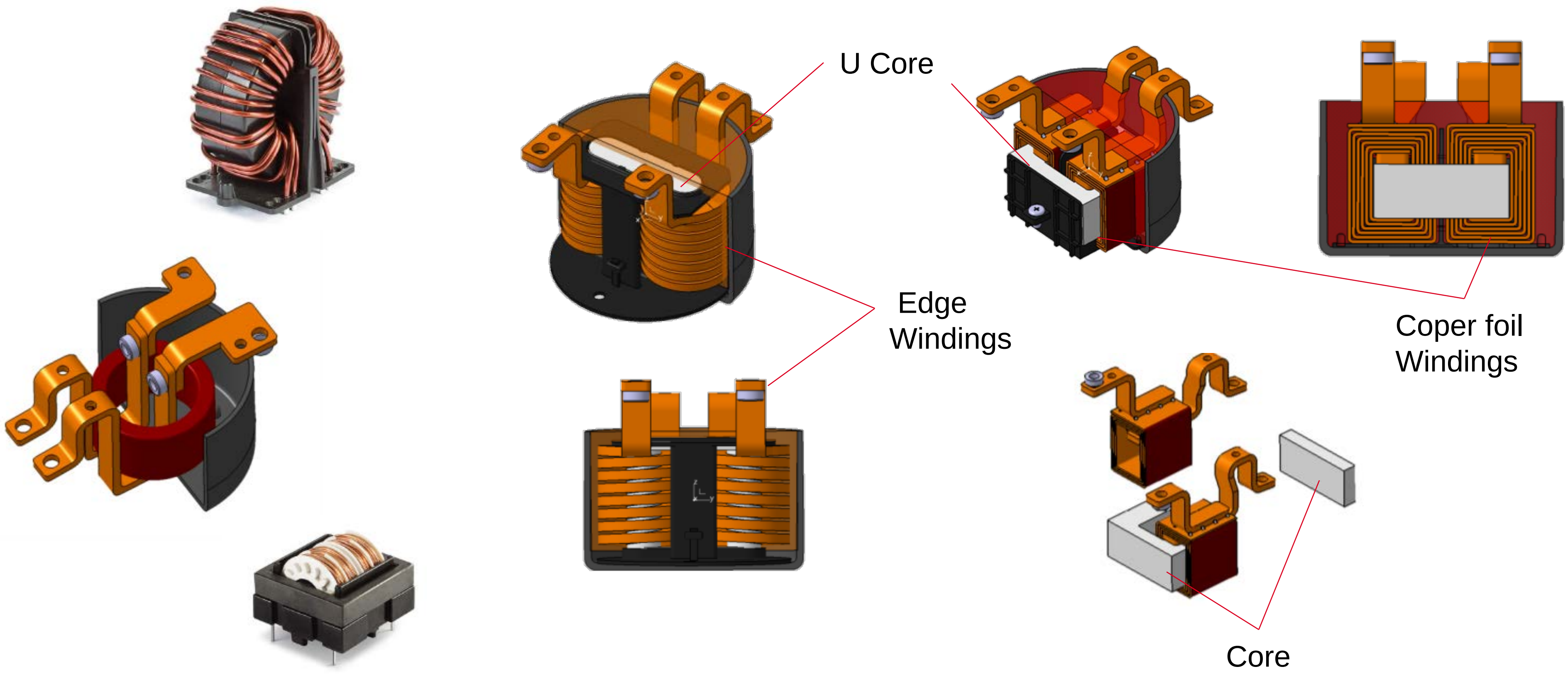
Equivalent scheme of EMI filter for Common Mode



Equivalent scheme of EMI filter for Differential Mode



Current-Compensated Choke Design Examples



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Properties of current-compensated choke vs. frequency depends on:

$$L_s = \frac{\mu' \mu_o A_e N^2}{l_e} \qquad R_s = 2\pi f \frac{\mu'' \mu_o A_e N^2}{l_e}$$

- Dimension and type of core, (cross section of core Ae, magnetic lenght of core l_e)
- Properties of magnetic material (permeability μ’, μ’’, magnetic flux B_s)
- Saturation properties
- Number of turns and method of winding (parasitic capacitance)

Comparison of Core Shape

No Airgap

Toroid

- ✓ The highest Ae/le ratio
- ✓ Highest impedance, AL value vs volume
- × Not suitable for winding large conductors

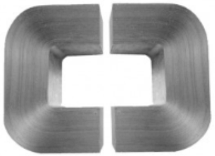
Oval

Frame

- ✓ Higher leakage inductance compared to toroid
- ✓ More space for windings
- × Lower impedance, AL vs volume compared to toroid

With Airgap

EE Planar



C core

U core

- ✓ Facility to assembly
- ✓ Good saturation properties
- × 40%-50% reduction of impedance, AL value
- × Worst mechanical stability

Assumptions:

- Core shape - toroidal
- Type of magnetic material – nanocrystalline and ferrite MnZn
- Dimension of ferrite core and nanocrystalline core are the same
- Different permeability
- The same number of turns
- To illustrate impact of the choke on the performance of the EMI filter, demo filter with 7 version of choke was tested
- Only difference was current-compensated choke

Ferrite

Nanocrystalline

Material	Ferrite				Nanocrystalline		
Choke	no.1	no.2	no.3	no.4	no.5	no.6	no.7
Permeability	15 000	10 000	5000	5000[1)]	100 000	70 000	50 000
Max. Flux Density [T] 25ºC/100ºC	0.40/0.17	0.41/0.21	0.44/0.3	0.44/0.3	1.2/1.1	1.2/1.1	1.2/1.1
Curie Temperature	110ºC	130ºC	140ºC	140ºC	600ºC	600ºC	600ºC
Operation Temperature	100ºC	120ºC	120ºC	120ºC	130ºC 150ºC	130ºC 150ºC	130ºC 150ºC
Dimension [mm]	63x38x28				65x40x28		
Turns	23	23	23	23	23	23	23
L@10kHz [mH] L@100kHz [mH] L@150kHz [mH]	15.2 5.0 3.5	10.4 5.4 3.4	7.4 7.9 8.6	7.4 8.0 8.7	56.6 9.1 6.4	48.4 16.23 10.6	29.8 14.3 9.8

Core of choke no.1, no.2, no.3 come from supplier A, no.4 supplier B, no.5, no.6, no.7 from supplier C

Magnetic Material Impact: Different Permeability

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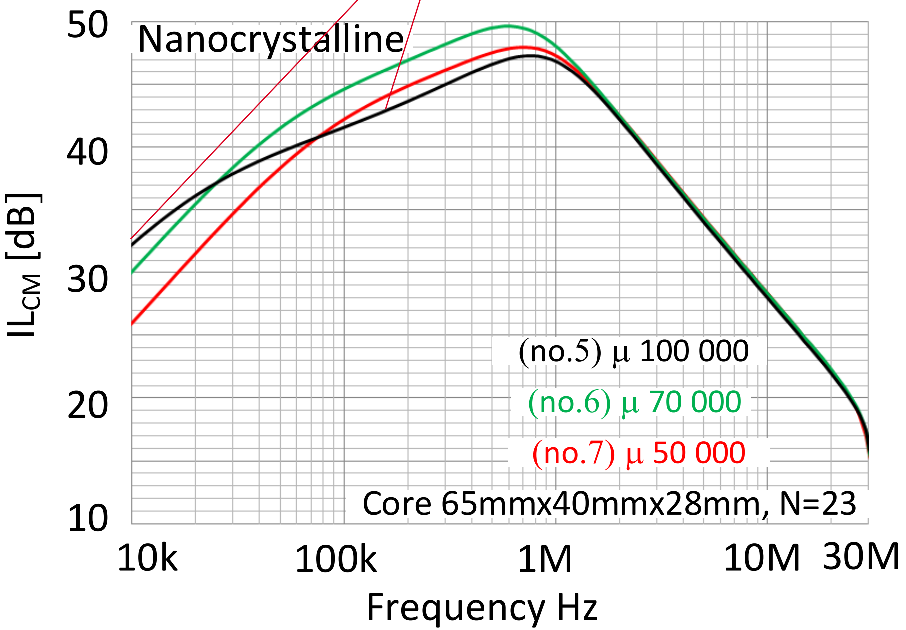
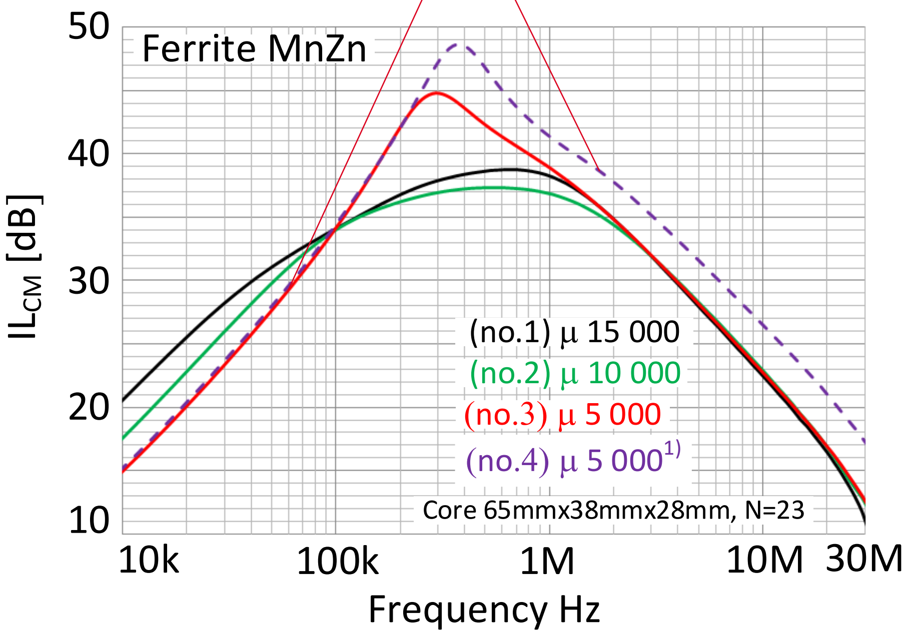
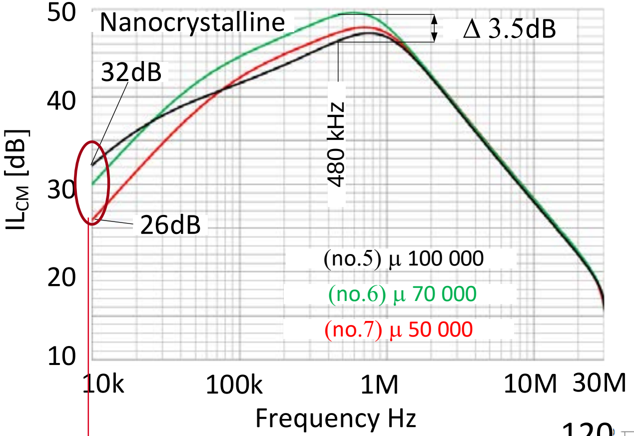
Choke no.5 µ100 000
Highest impedance @10kHz
The lowest impedance @ 150kHz

Choke no.3 & no.4 µ 5000
The same impedance up to 100kHz
Differences above 300kHz





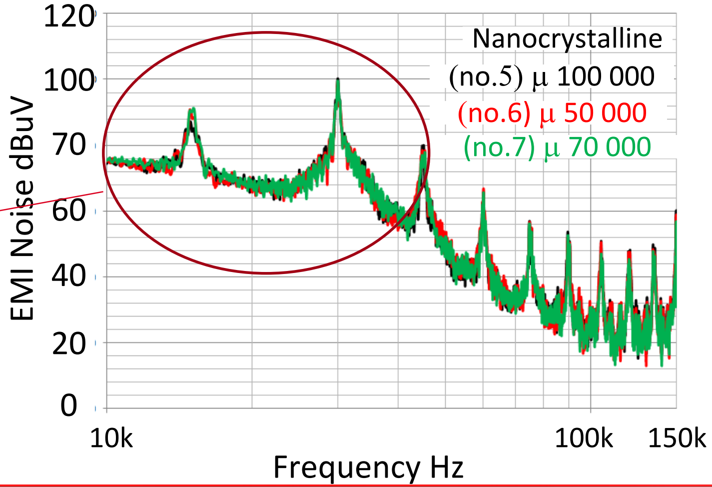
Magnetic Material Impact (Nanocrystalline): Different Permeability

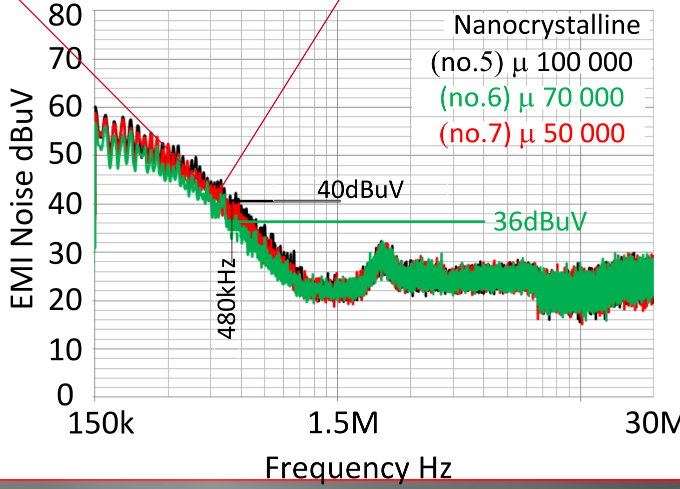


The level of EMI noise is the highest for high permeability material (µ100 000).

The EMI noise level of choke no.7 µ50 000 is similar than no.5 µ100 000

No impact on EMI noise level





Magnetic Material Impact (Ferrite MnZn): Different Permeability

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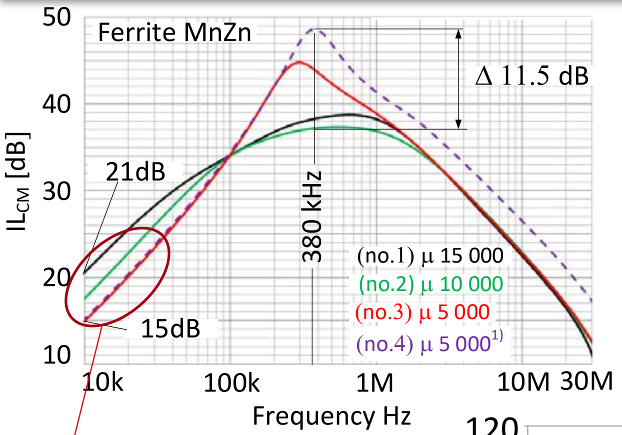
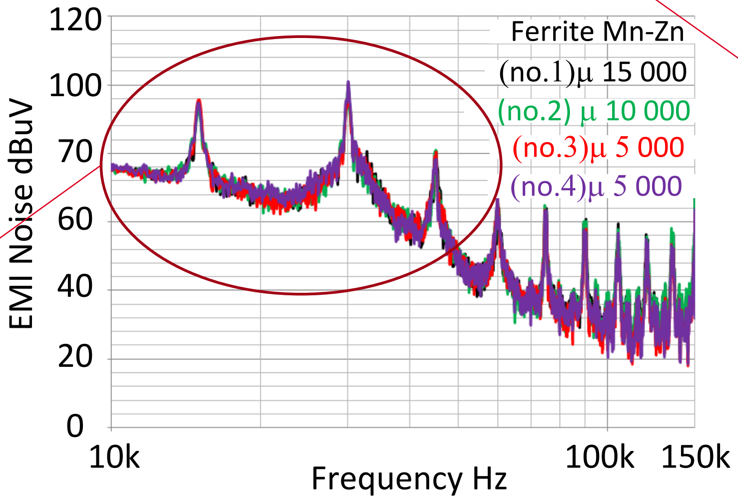
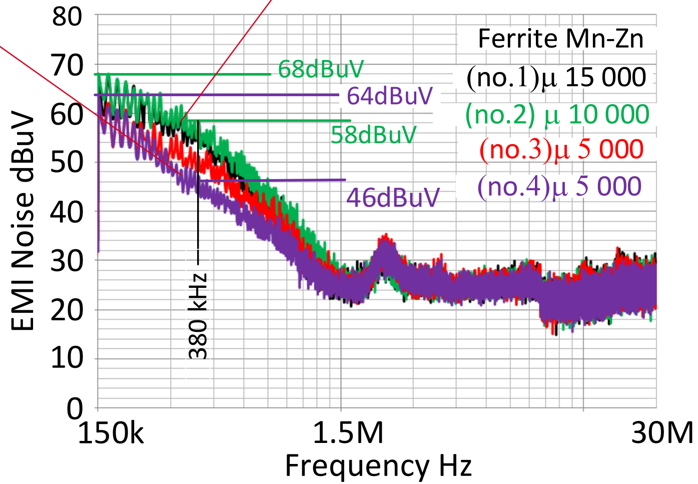


EMI noise is the lowest with low permeability material

No EMI noise differences for choke with permeability µ15 000 and µ10 000



No impact
on EMI noise level

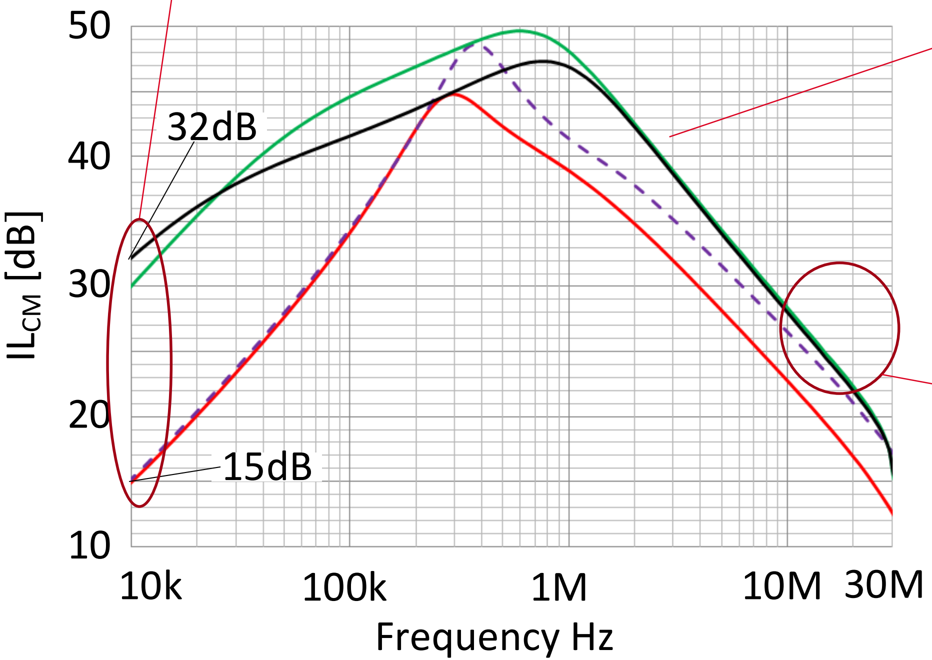


Ferrite
63x38x28mm
N=23

Nanocrystalline
65x40x28mm
N=23

Very high impedance of choke made out of nanocrystalline material

Impedance of choke no.4 (ferrite) is higher than no.5 (nanocrystalline) between 250 kHz and 500 kHz

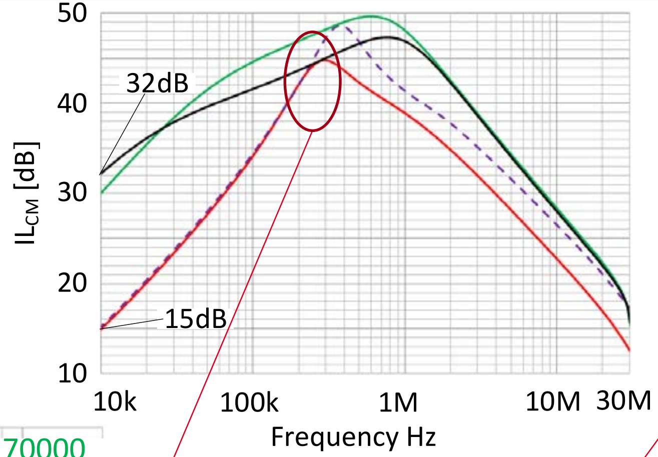


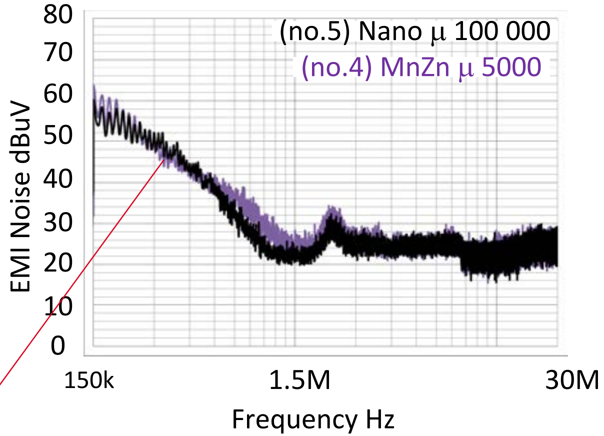
The impedance is similar in MHz range

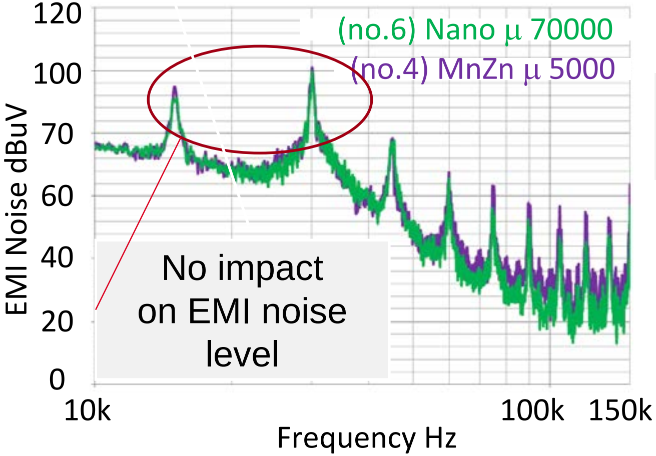
Magnetic Material Impact: Comparision Nanocrystalline vs. Ferrite

Ferrite
63x38x28mm
N=23

Nanocrystalline
65x40x28mm
N=23

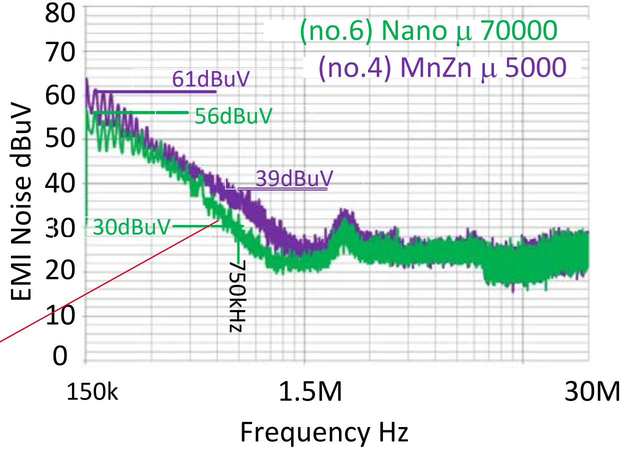






No impact on EMI noise level

No differences between 200-300 kHz



Maximum noise reduction between 750 kHz-1 MHz

Saturation due to common mode current:

Ferrite MnZn µ5000 | Nanocrystalline µ50 000

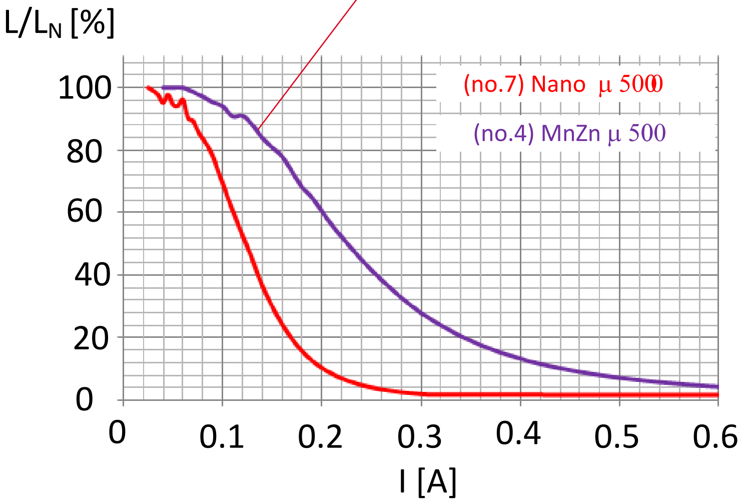
$$I_{s1} = \frac{B_{s1} l_{e1}}{\mu_e \mu_1 N_1} \qquad I_{s2} = \frac{B_{s2} l_{e2}}{\mu_e \mu_2 N_2}$$

$$l_{e1} \approx l_{e2}$$

$$N_1 = N_2$$

$$\frac{I_{s1}}{I_{s2}} = \frac{B_{s1}}{B_{s2}} \frac{\mu_2}{\mu_1}$$

Saturation current is higher for ferrite



The saturation current of nanocrystalline core will be higher only if permeability of cores will be equal

Saturation due to volt-time product:

Ferrite MnZn µ5 000

Nanocrystalline µ50 000

$$\int V_1\,dt = N_1 B_{S1} A_{e1}$$

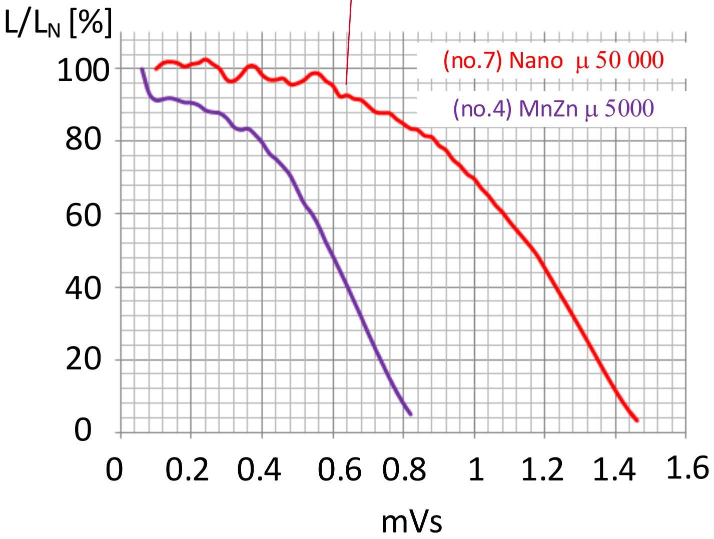
$$\int V_2\,dt = N_2 B_{S2} A_{e2}$$

$$N_1 = N_2$$

$$A_{e1} \approx A_{e2}$$

$$\frac{\int V_1\,dt}{\int V_2\,dt} = \frac{B_{s1}}{B_{s2}}$$

The nanocrystalline is more immune to saturation than ferrite.



Impact of Winding Method on Current – Compensated Choke Properties

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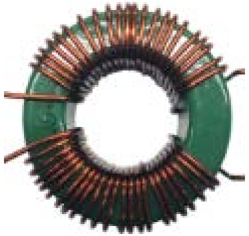
Assumptions:



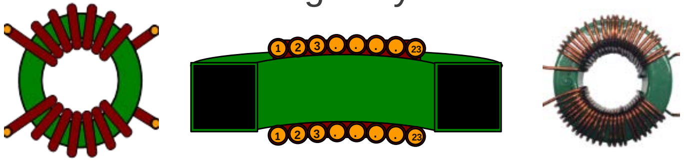
single layer

double layer

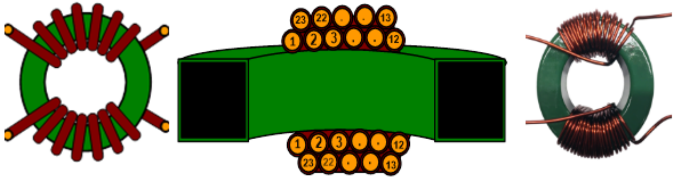
``bifilar``

- Core shape -toroidal
- Material- ferrite 15 000
- Core dimension 63x38x28 mm
- The number of turns is 23
- Three methods of winding are compared, single layer, double layer, ``bifilar``
- The ``bifilar `` winding is made with cable with silicon isolation to achieve required isolation
- To illustrate impact of the choke on the performance of the EMI filter, demo filter with 3 version of choke was tested
- Only difference was current compensated choke

Single layer



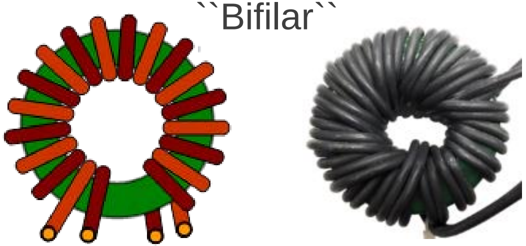
Double layer



- ✓ Good attenuation at high frequency
- × Require more space for windings

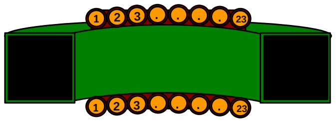
- ✓ Require less space for windings
- × Less attenuation at high frequency

``Bifilar``

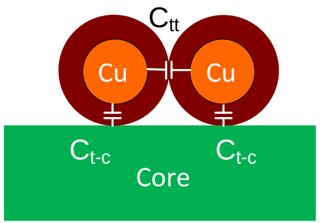


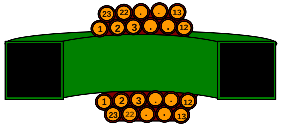
- ✓ Good attenuation at high frequency
- × Require more space for windings
- × Low attenuation at low frequency
- × Require cable with thicker isolation

Impact of Winding Method on Current – Compensated Choke Properties

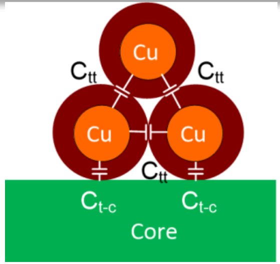


Single layer





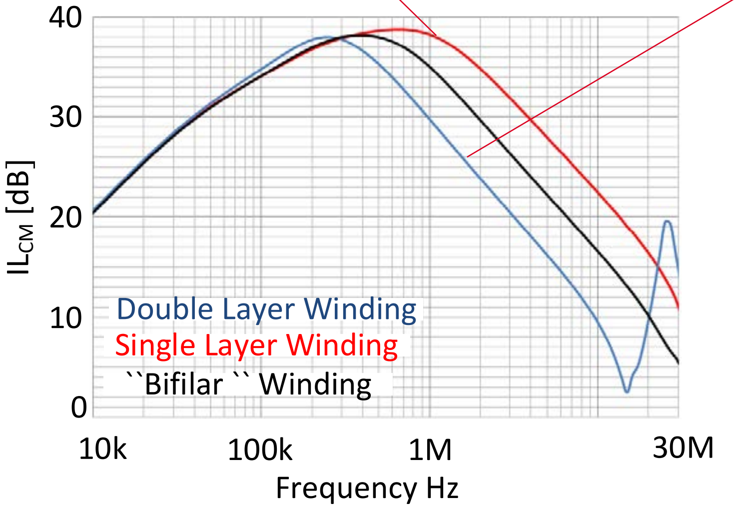
Double layer

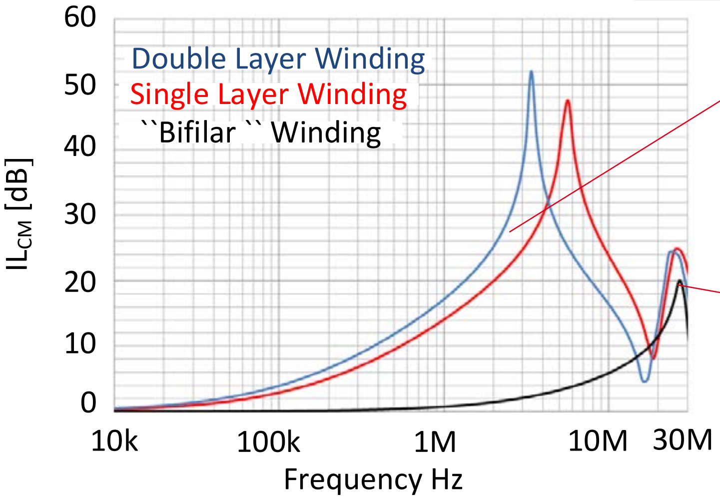


Low value of parasitic capacitance

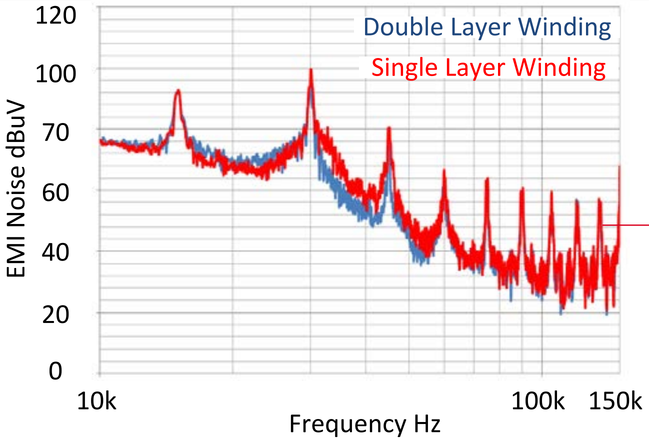
High value of parasitic capacitance

High value of leakage inductance

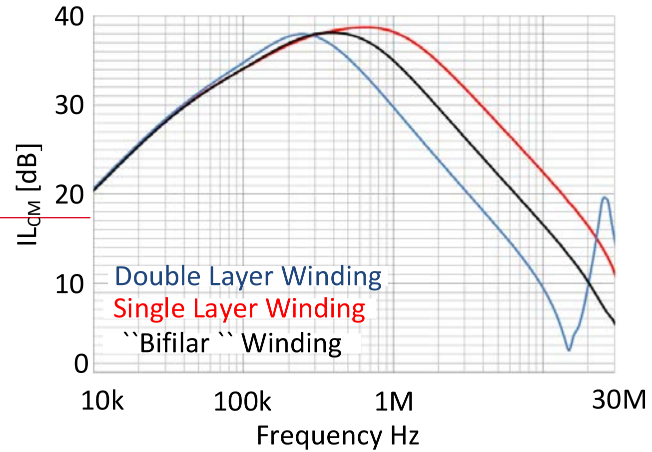


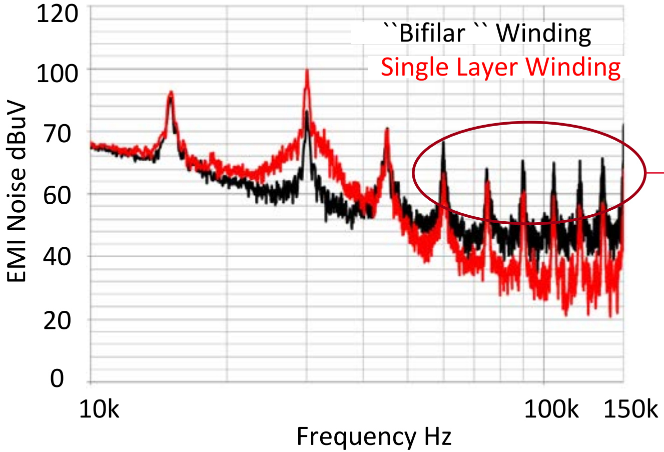


Low value of leakage inductance

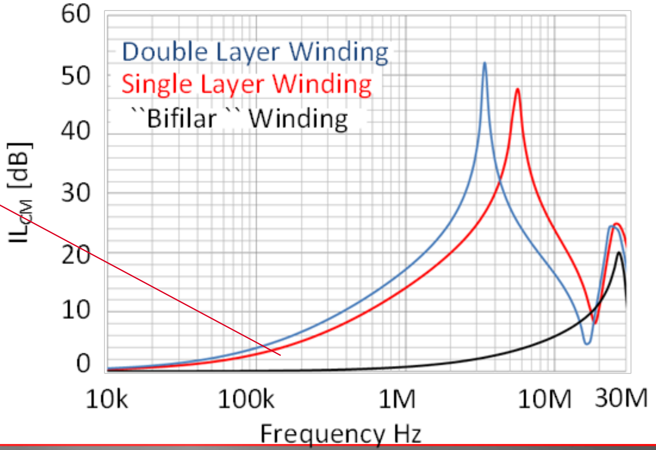


No impact on EMI level up to 150kHz

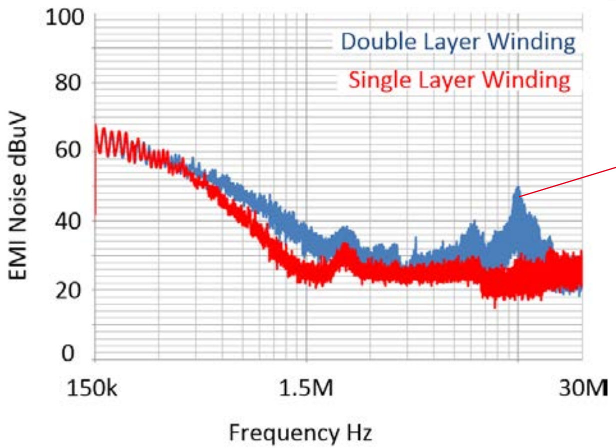




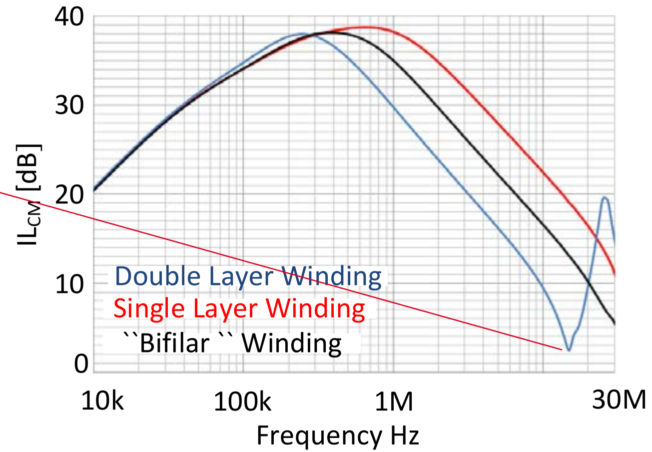
Impact of low leakage inductance

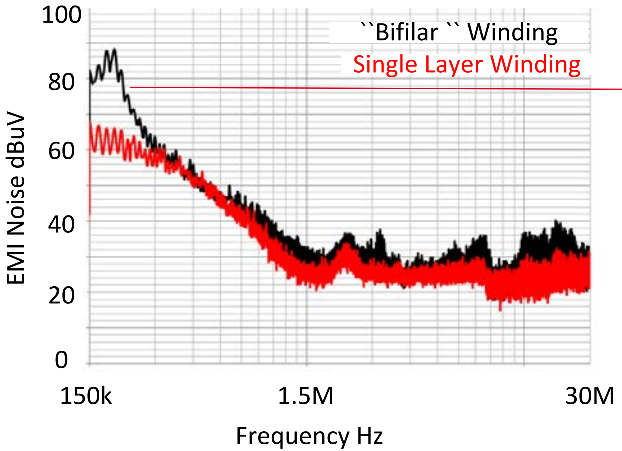


Impact of Winding Method on Current – Compensated Choke Properties

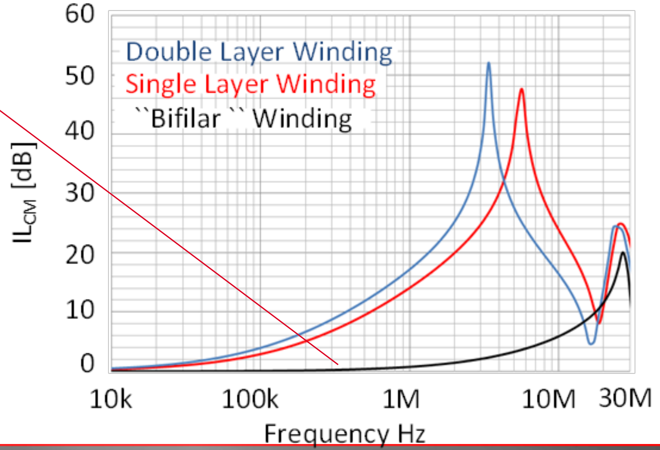


Impact of parasitic capacitance





Impact of low leakage inductance



Conclusion

- **Core shape**
  - Toroid cores have highest CM impedance, AL vs. volume, low leakage inductance but difficult to wind big wires
  - Rectangular cores have higher leakage inductance and more space for winding but lower impedance, AL
  - Cores with air gap have reduction by 50% of CM insertion loss
- **Core material**
  - A high permeability material does not guarantee high EMI noise reduction at all frequencies
  - Lower permeability material more often gives better EMI noise reduction above 150kHz
  - Chokes with nanocrystalline material have higher CM insertion loss below 150 kHz compared to ferrite. However nanocrystalline are no better than ferrite when DM noise dominates
  - Nanocrystalline cores are ca 5 times expensive than ferrite

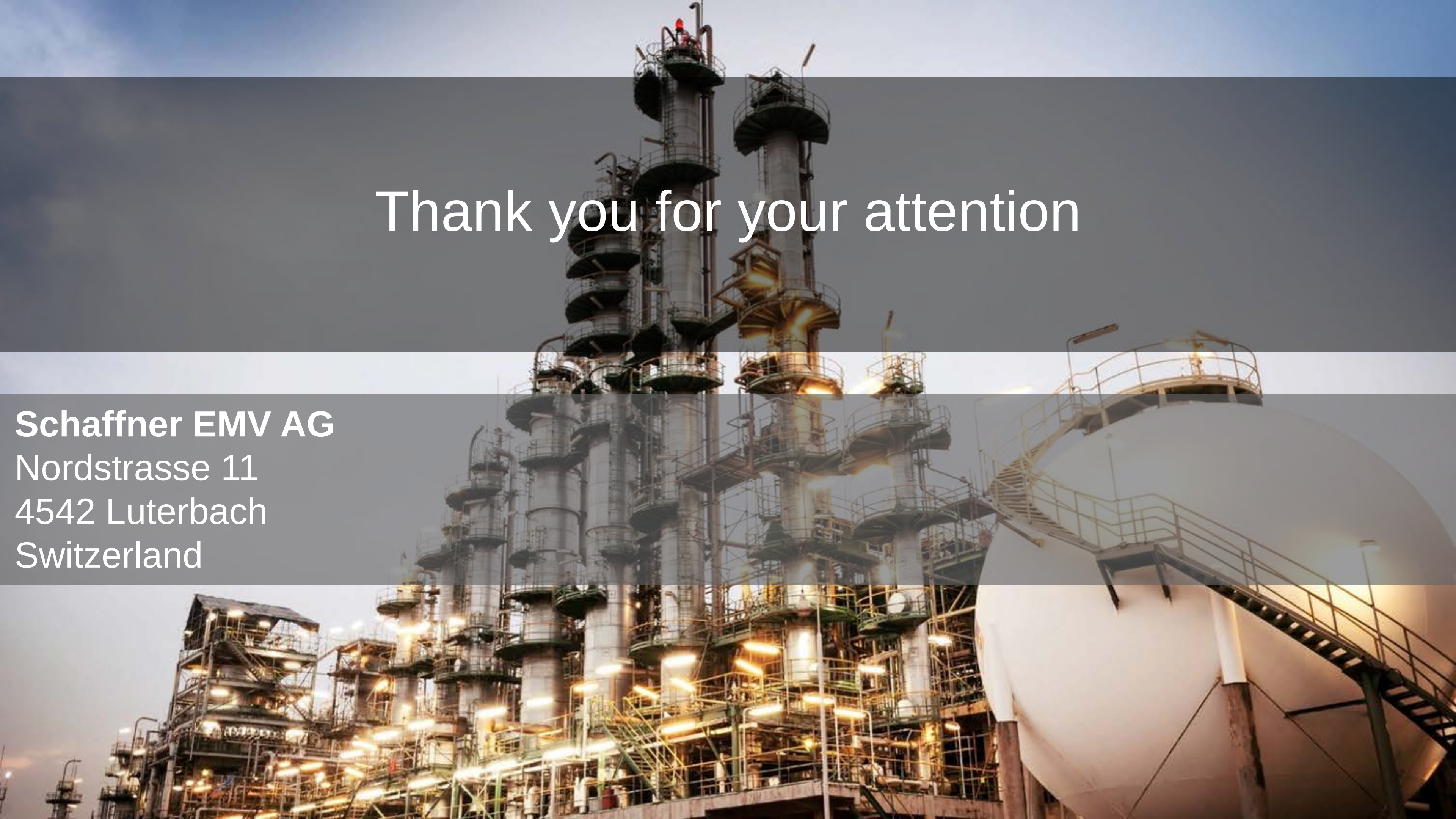
Saturation properties

- Saturation current is proportional to the ratio Bs/µ when le and N are not changed
- Maximum flux density B_s for nanocrystalline is always higher than that for ferrite (ca 3 times), but if µ for nanocrystalline is much higher than that for ferrite then saturation current for the ferrite will be the higher
- Then nanocrystalline is more immune to saturation than ferrite if saturation is due to volt-time product. However if N and Ae are significantly reduced the advantage of nanocrystalline can be negated

Conclusion

Method of Winding

- Single layer winding has the highest EMI noise reduction at high frequencies due to the lowest value of parasitic capacitance
- Double layer winding has less EMI noise reduction at high frequencies due to higher parasitic capacitance. Therefore EMI noise is higher at high frequency range
- Bifilar winding has less parasitic capacitance but needs more space due to thicker insulation
- Bifilar has low leakage inductance so DM noise is higher especially at low frequencies (up to 300kHz)



Thank you for your attention

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