EMI Conducted and Radiated Emissions

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ADVANCED MATERIALS – THE KEY TO PROGRESS

APEC

30 years
1985-2015

Abstract

This presentation overviews the EMC Conducted and Radiated Emissions challenges that will be presented as the power electronics market migrates to high frequency IGBT solutions. The presentation will cover the following topics:

-EMI Standards

-Topology Design Ideas to minimize EMI

-EMI conducted emissions filter topology design (common mode chokes, differential mode chokes, X and Y capacitors).

-Potential solutions for solving high frequency radiated emissions

Importance of EMC

- Electromagnetic Compatibility (EMC) requires that systems/equipment be able to tolerate a specified degree of interference and not generate more than a specified amount of interference
- EMC is becoming more important because there are so many more opportunities today for EMC issues

- Increased use of electronic devices
  - -Inverters for Alternate Energy and Automotive applications
  - -Drives for HVAC, Appliance, Pool Pump, etc
  - -Personal computing/entertainment/communication

- Increased potential for susceptibility/emissions
  - -Lower supply voltages
  - -Increasing switching frequencies (SiC IGBT / Mosfets)
  - -High swiching currents (ie 1MW solar inverters)
  - -Increasing packaging density
  - -Demand for smaller, lighter, cheaper, lower-power devices

Impact of SiC FET on EMI

Compared to the conventional Si devices, the switching speed of SiC FET can be two to six times higher. This leads to a significantly higher voltage and/or current overshoot during the switching transients. Previous research has shown that in specific circuit configurations, the high-frequency noise level of an SiC JFET-based motor drive system can be 20 dB higher than that of a comparable Si insulated gate bipolar transistor (IGBT) based motor drive.

Furthermore, with the increased high-frequency contents, the influence of previously negligible circuit parasitics starts to play an increasing role in EMI production.

Even though all of the previous research unanimously concludes that SiC power devices increase the level of EMI noise , a quantitative understanding of the SiC source and its differences with Si is still elusive.

(IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 29, NO. 4, APRIL 2014 , Comparison and Reduction of Conducted EMI in SiC JFET and Si IGBT-Based Motor Drives
Xun Gong, *Member, IEEE*, and Jan Abraham Ferreira, *Fellow, IEEE)*

EMC Requirements

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Federal Regulations Commission (FCC) www.fcc.gov
Title 47: Telecommunications
Part 15: Subpart B regulates "unintentional" Radio Frequency
FCC regulates radio, TV, wire, satellite and cable devices

Section 15.3 Definitions

(h) Class A digital device. A digital device that is marketed for use in a commercial, industrial or business environment, exclusive of a device which is marketed for use by the general public or is intended to be used in the home.

(i) Class B digital device. A digital device that is marketed for use in a residential environment notwithstanding use in commercial, business and industrial environments. Examples of such devices include, but are not limited to, personal computers, calculators, and similar electronic devices that are marketed for use by the general public. Note: The responsible party may also qualify a device intended to be marketed in a commercial, business or industrial environment as a Class B device, and in fact is encouraged to do so, provided the device complies with the technical specifications for a Class B digital device. In the event that a particular type of device has been found to repeatedly cause harmful interference to radio communications, the Commission may classify such a digital device a digital device, regardless of its intended use.

Section 15.107 Class B Conducted limits

(a) Except for Class A digital devices, for equipment that is designed to be connected to the public utility (AC) power line, the radio frequency voltage that is conducted back onto the AC power line on any frequency or frequencies within the band 150 kHz to 30 MHz shall not exceed the limits in the following table, as measured using a 50 µH/50 ohms line impedance stabilization network (LISN). Compliance with the provisions of this paragraph shall be based on the measurement of the radio frequency voltage between each power line and ground at the power terminal. The lower limit applies at the band edges.

Frequency of Emission (MHz)	Conducted Limit (dBuV)	
	Quasi-peak	Average
0.15-0.5	66 to 56 *	56 to 46 *
0.5-5	56	46
5-30	60	50

* Decreases with the logarithm of the frequency.

Source: www.ecfr.gov

Section 15.107 Class A Conducted limits

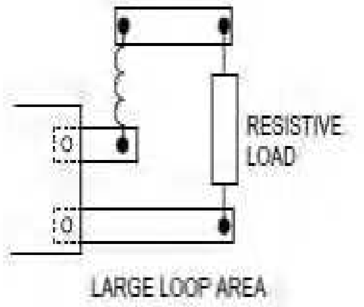
(b) For a Class A digital device that is designed to be connected to the public utility (AC) power line, the radio frequency voltage that is conducted back onto the AC power line on any frequency or frequencies within the band 150 kHz to 30 MHz shall not exceed the limits in the following table, as measured using a 50 μH/50 ohms LISN. Compliance with the provisions of this paragraph shall be based on the measurement of the radio frequency voltage between each power line and ground at the power terminal. The lower limit applies at the boundary between the frequency ranges.

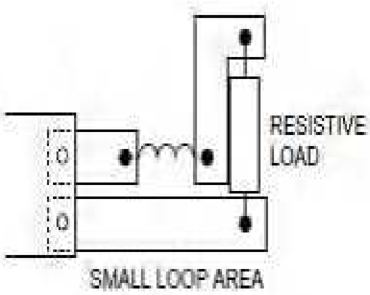
Frequency of Emission (MHz)	Conducted Limit (dBuV)	
	Quasi-peak	Average
0.15-0.5	79	66
0.5-30	73	60

Source: www.ecfr.gov

EMI Reduction Design Techniques

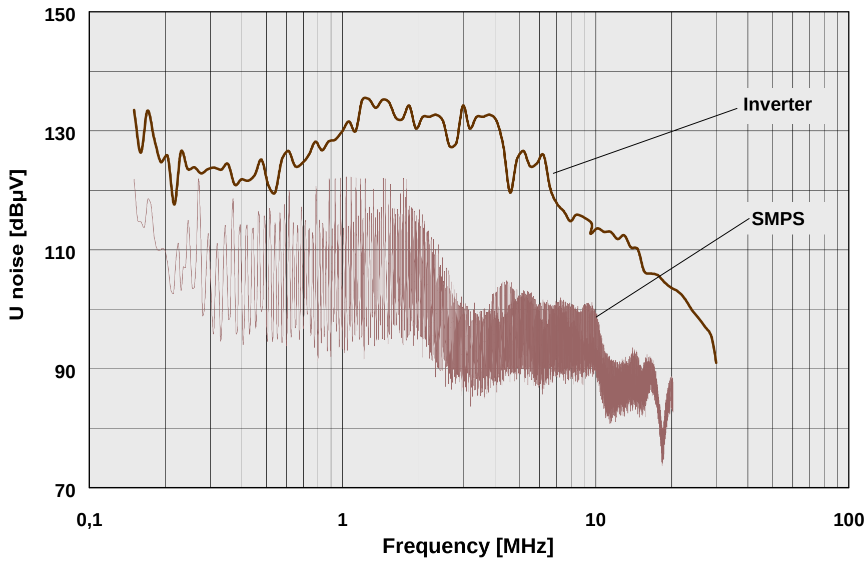
- Keep current loops small. The ability of a conductor to couple energy by induction and radiation is lowered with a smaller loop, which acts as an antenna
- For pairs of copper printed circuit (PC) board traces, use wide (low impedance) traces aligned above and below each other.
- Locate filters at the source of interference, basically as close to the power module as possible.
- Filter component values should be chosen with consideration given to the desired frequency range of attenuation. For example, capacitors are self-resonant at a certain frequency, beyond which they look inductive. Keep bypass capacitor leads as short as possible.
- Locate components on the PC board with consideration given to proximity of noise sources to potentially susceptible circuits.
- As close as possible decoupling capacitors should be located to the converter, especially X and Y capacitors.
- Use ground planes to minimize radiated coupling, minimize the cross-sectional area of sensitive nodes, and minimize the cross-sectional area of high current nodes that may radiate such as those from common mode capacitors
- Surface-mount devices (SMD) are better than leaded devices in dealing with RF energy because of the reduced inductances and closer component placements available.

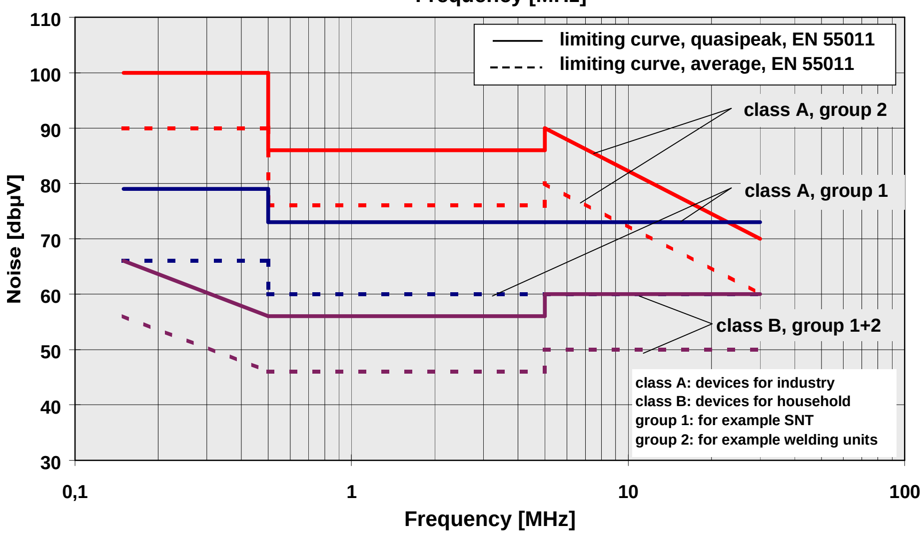


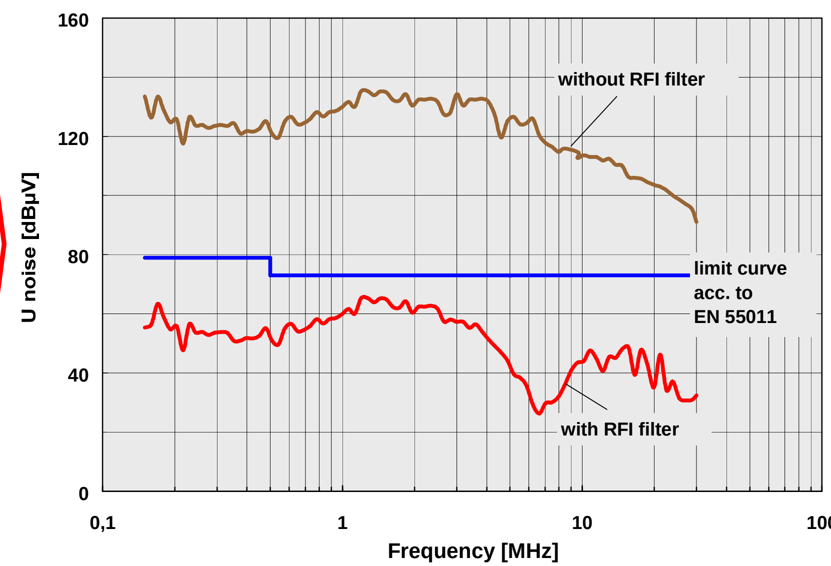


EMI is more dependent on layout than topology

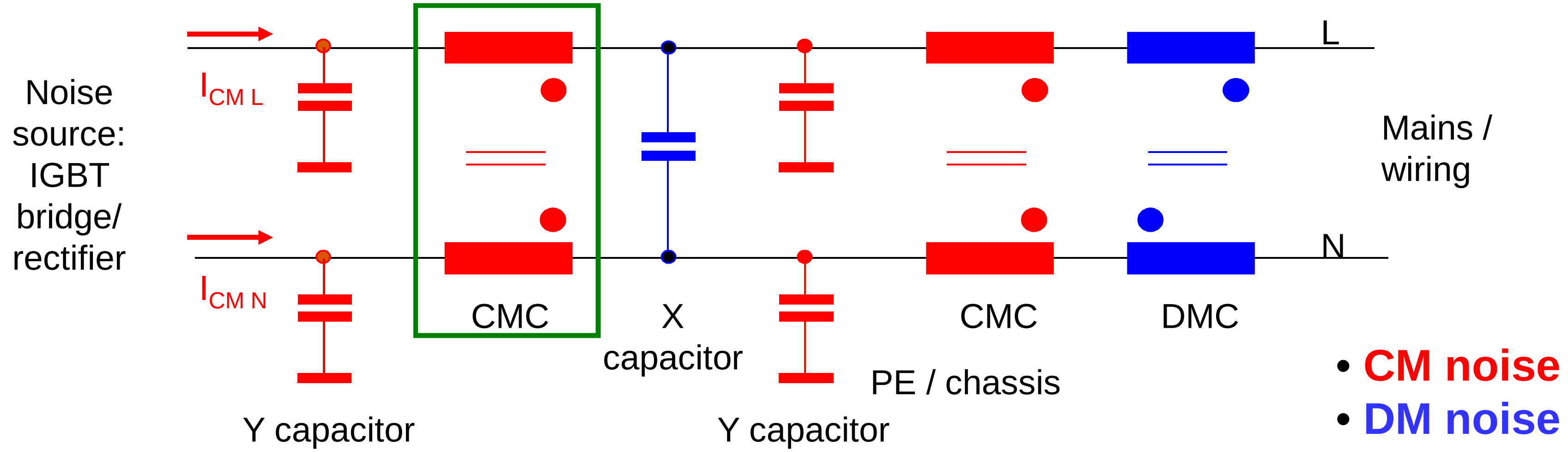
Function of the EMI Filter





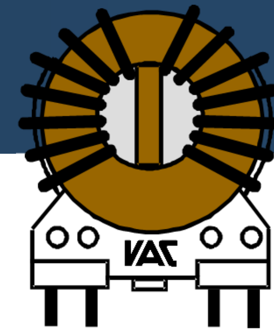


EMI Filter Topology

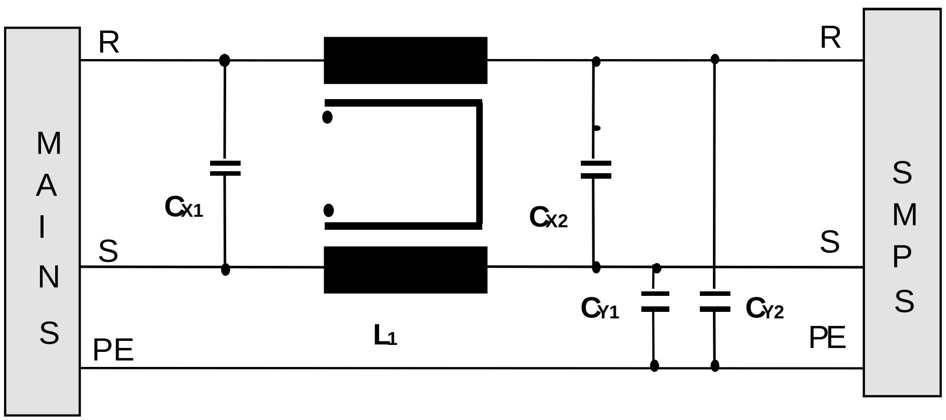


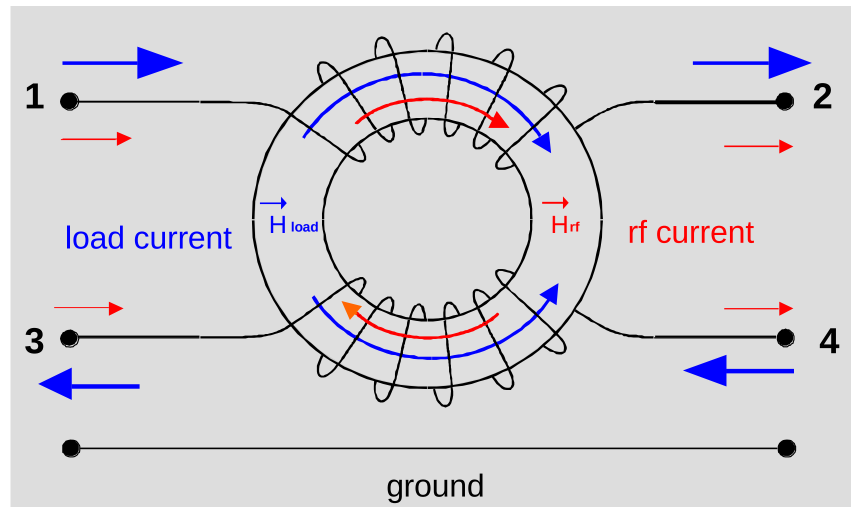
- Typical EMI filter incorporates common mode inductors, differential mode inductors and X and Y capacitors.
- The inductors become high impedances to the high frequency noise and either reflect or absorb the noise.
- The Y capacitors become low impedance paths to ground and redirect the CM noise away from the main line.
- The X capacitors return the noise from L to N and prevent the DM noise from reaching the connection to the grid.
- To be effective the common mode inductor must provide the proper impedance over the frequency range.
- As a starting point the filter should have lots of attenuation at the main switching frequency of the converter as this is the strongest source of EMI.

Common Mode Choke



Operational principle of the CMC



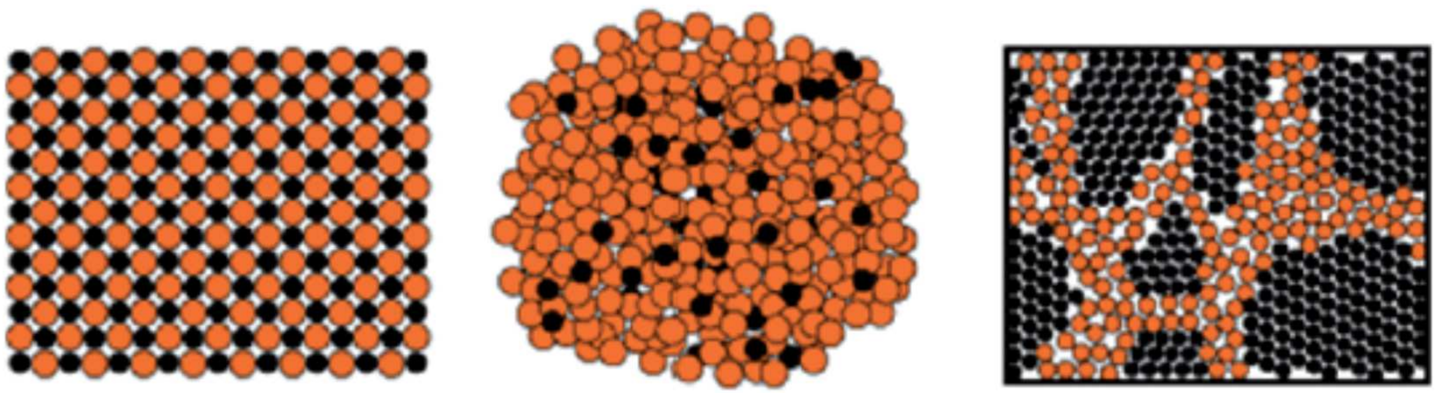


- equal number of turns wound in opposite direction. The line currents in each winding create fluxes that are equal in mangnitude but opposite in phase thus cancelling each other.
- only slight attenuation of symmetrical currents.
- strong “common-mode” damping against asymmetric currents.
- µ must be safe against unbalanced currents and Bs defines the operating limit.

Nanocrsytalline Cores

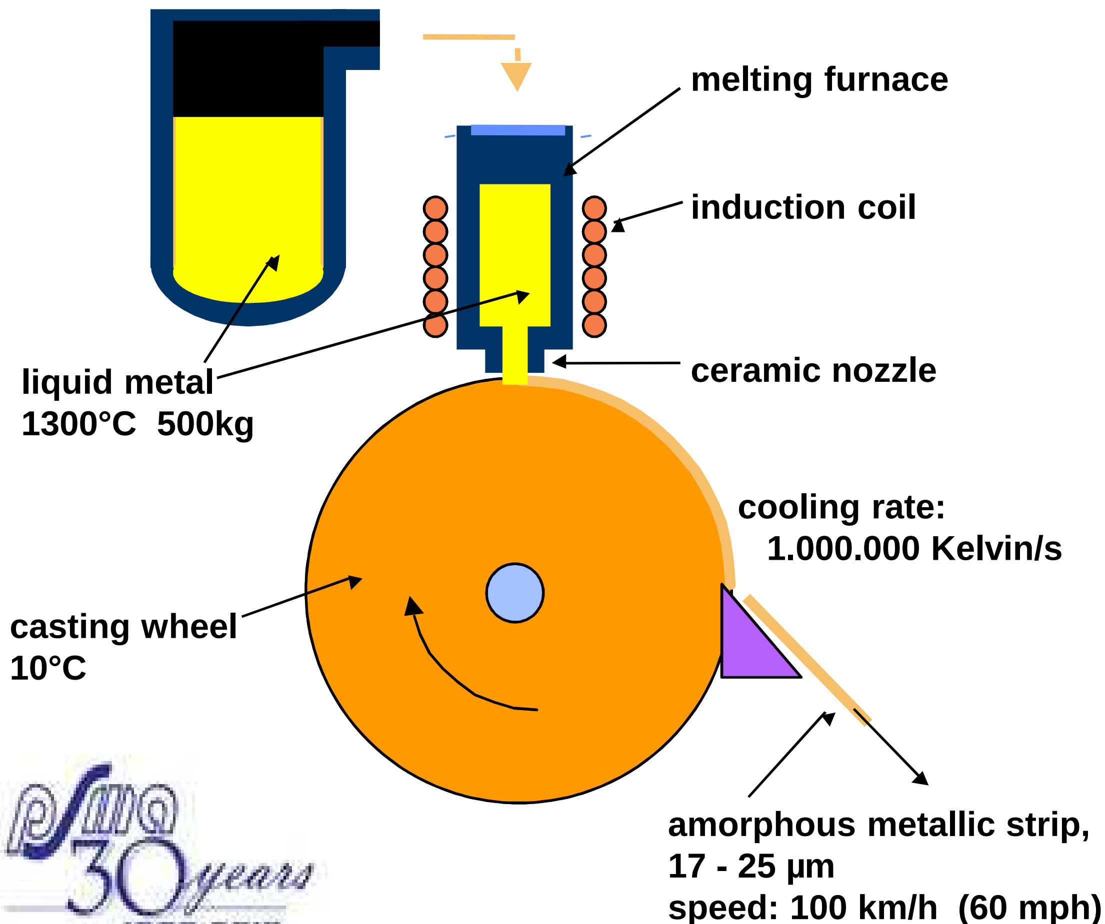
Material structure (atoms)

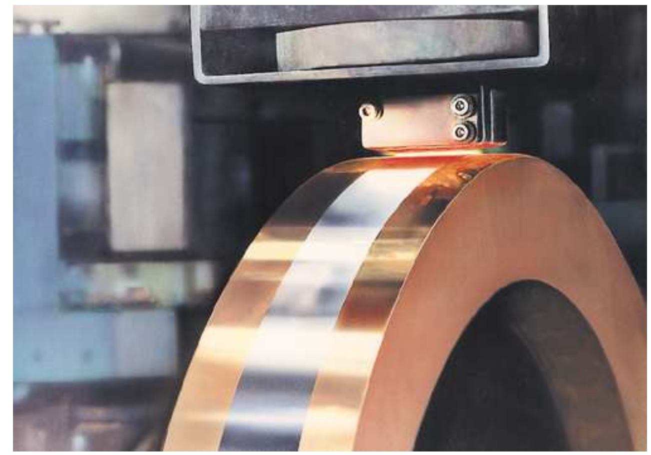
- (1) Crystalline
- (2) Amorphous
- (3) Nanocrystalline

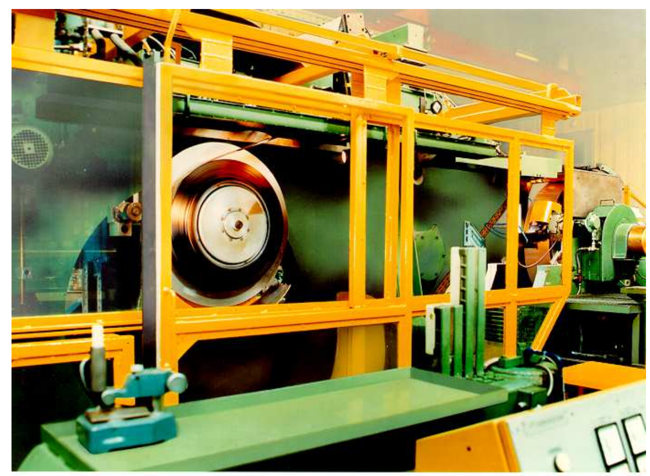


(1) (2) (3)

Rapid Solidification process for amorphous strip



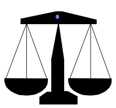


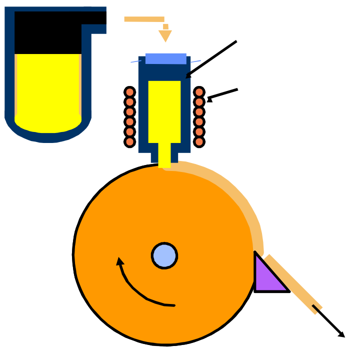


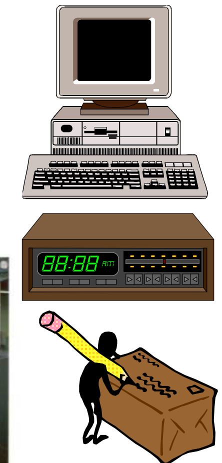
Nanocrystalline Core Production

Strip production

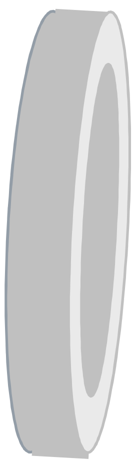
Core production



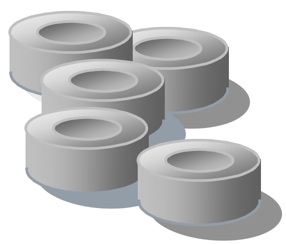




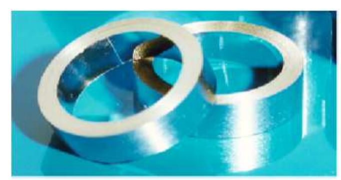
Raw Material

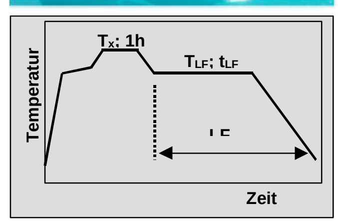


Amorphous strip coils

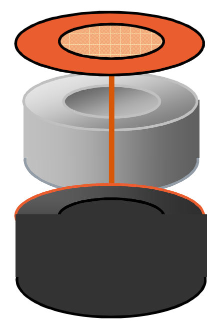


Core winding

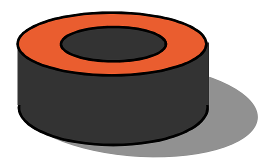




Heat treatment magnetics



Casing, coating



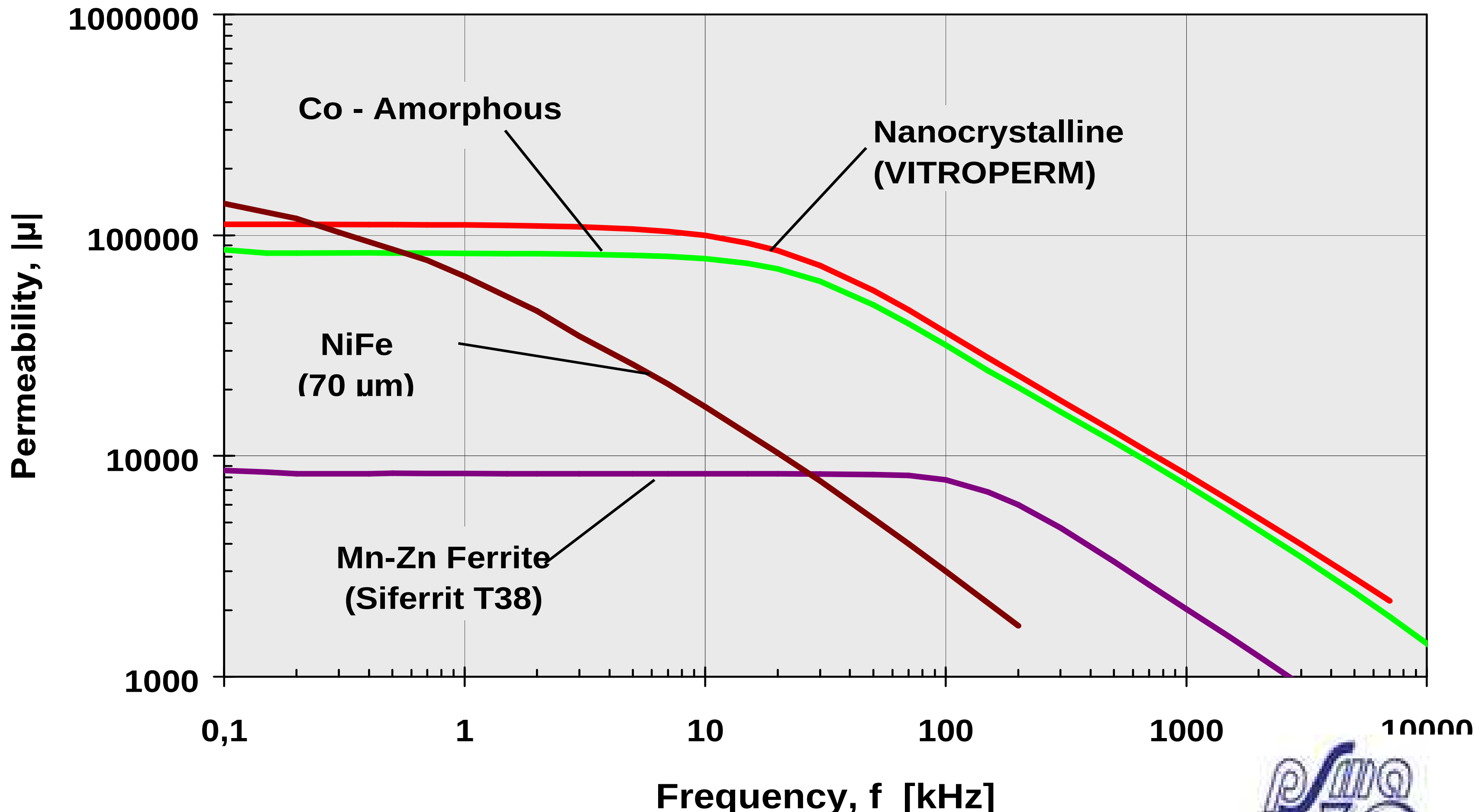
Testing, packing, transport

Material Properties

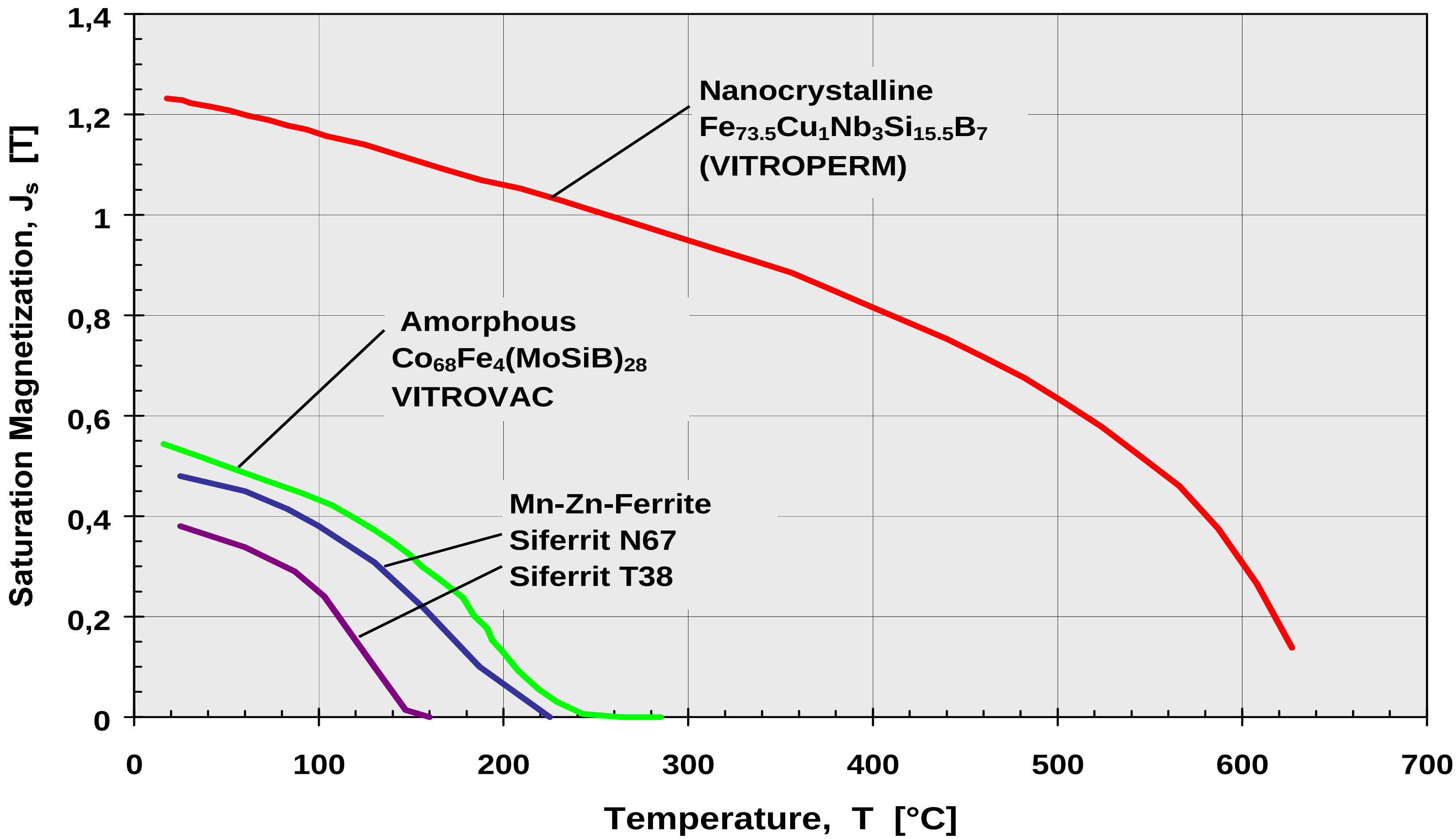
Material	**Ferrite**	**Nanocrystalline**
Material basis	MnZn	**~ 73.5% Fe**
Permeability µr,max (10kHz)	< 15.000	**15.000…> 100.000**
Losses $p_{Fe, typ.}$(100kHz, 0.3T, 20°C)	185 W/kg (C94, N92)	**85 W/kg**
Saturation induction B_s	0.4 T	**1.2 T**
Curie temperature T_C	200…300 °C	**600 °C**
Upper continuous operation temperature	100 °C	**150…180 °C**

Magnetic Properties

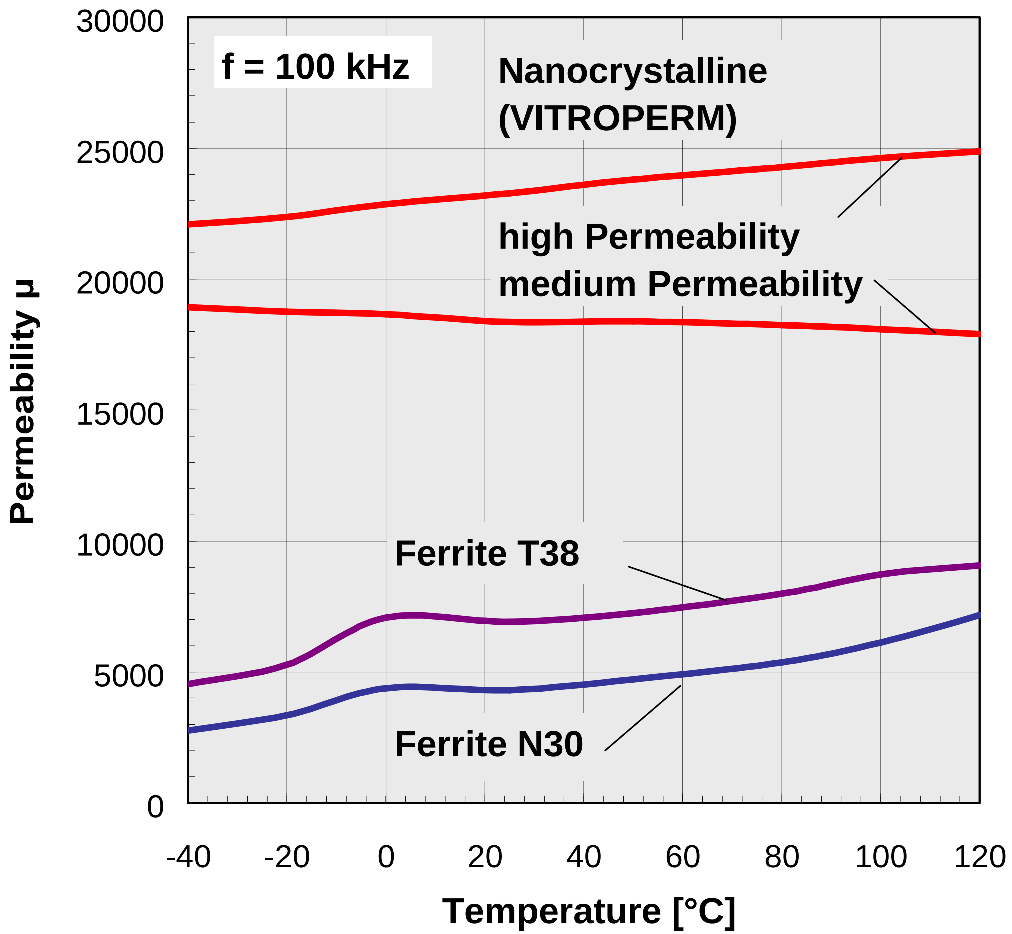
Z = F … = (… f … / … N … / …)(μ“+jμ‘)

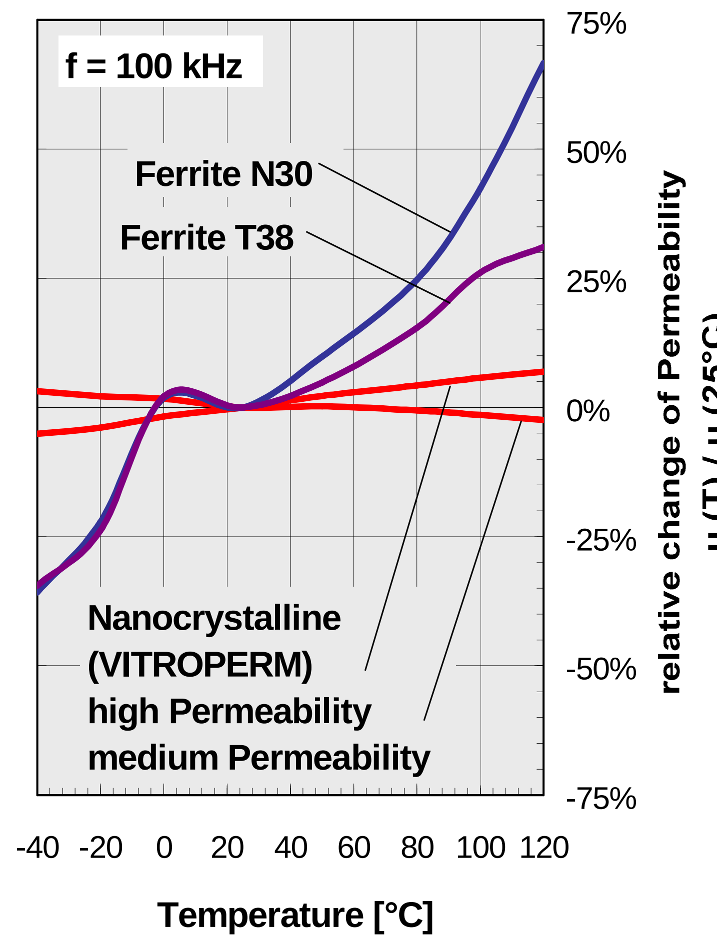


Nanocrystalline = high B_s and extended T - range (> 120 °C)



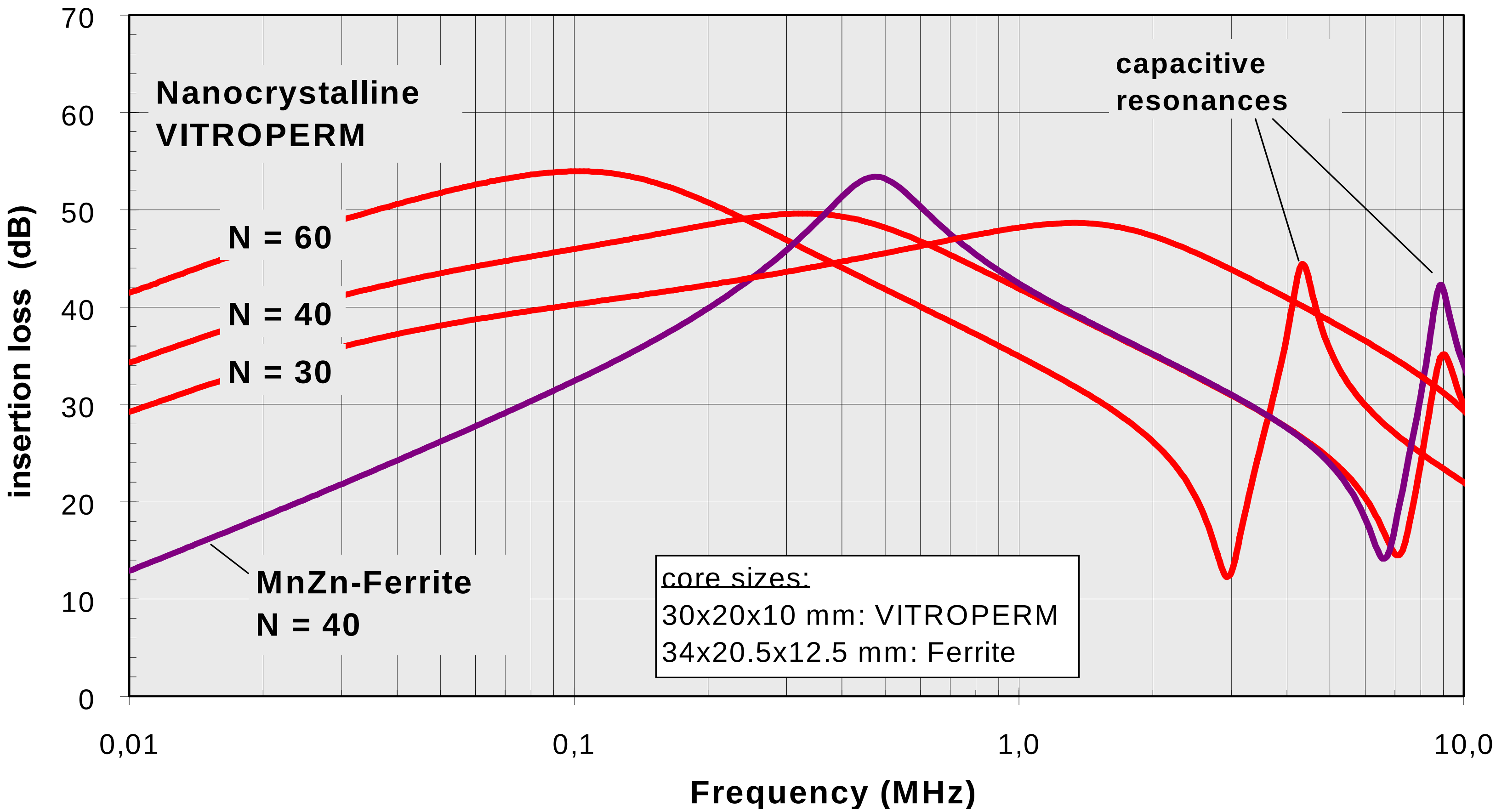
Nanocrystalline = excellent thermal stability, easy design



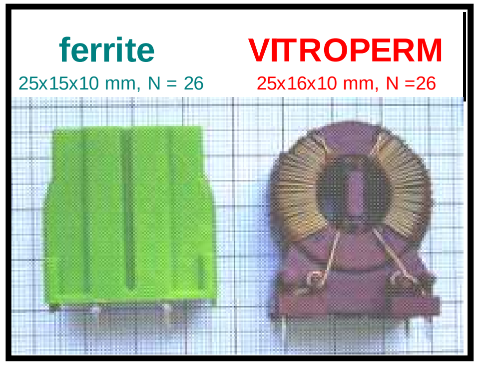


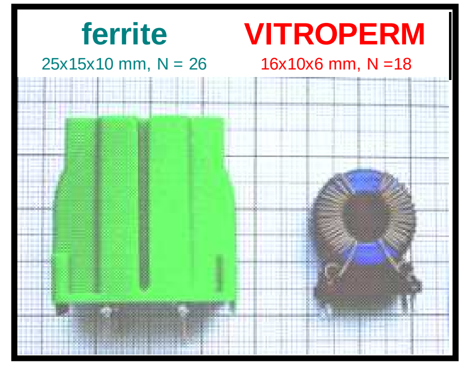
EMC Properties

Nanocrystalline = broadband loss spectrum, high damping already at „low" frequencies, lower # of turns...



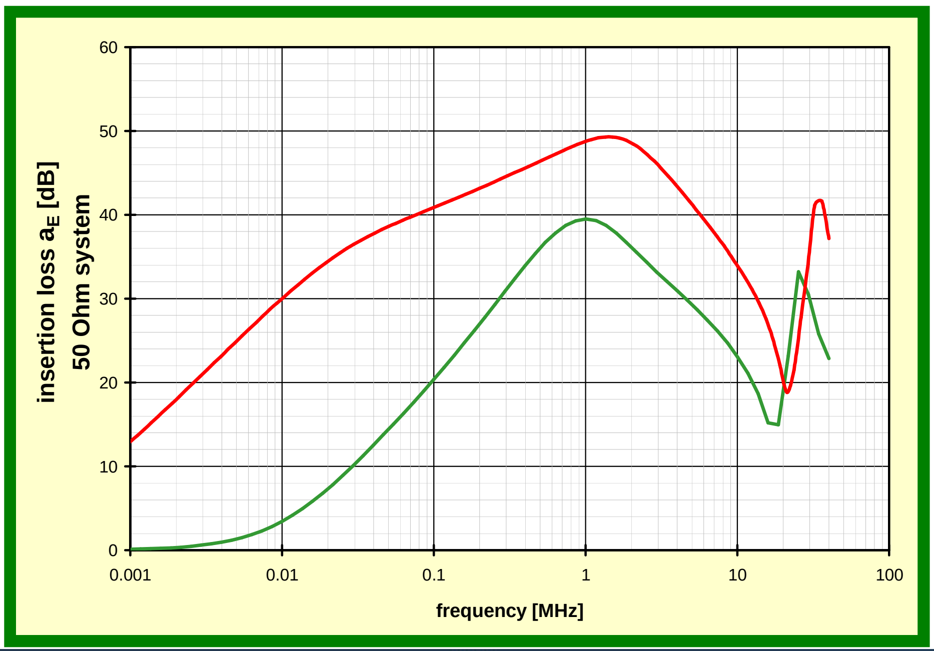
EMC Properties

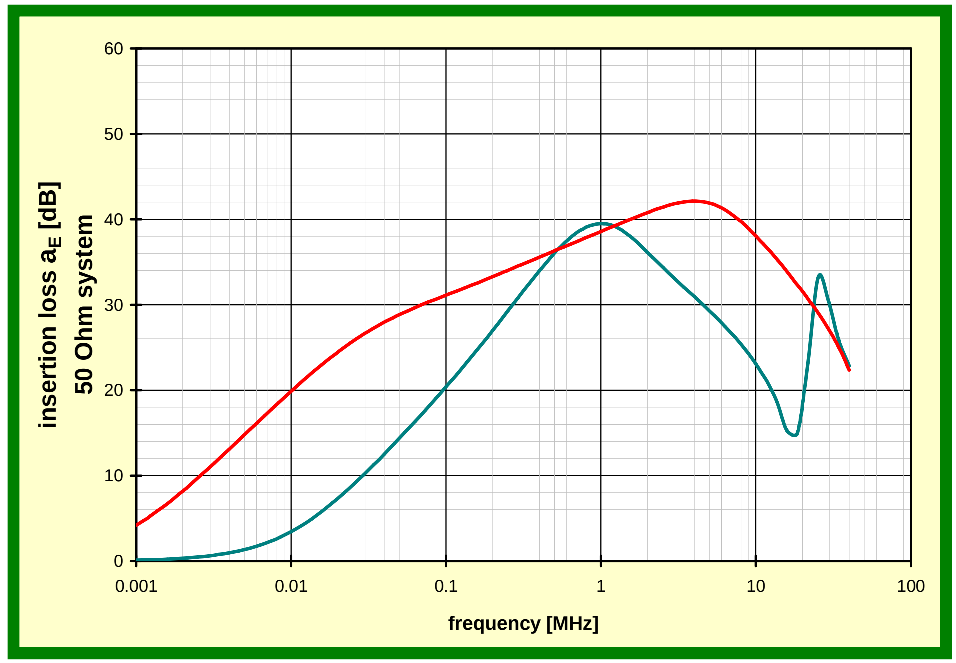




Nanocrystalline = better insertion loss in same volume...

and similar loss in smaller volume





Ferrite vs Nanocrystalline Design Criterium

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Ferrite Advantages

- Cost
- Various Form factors available
- Lower u cores can offer lower susceptibility to saturation for unbalanced currents (Nanocrystalline however can handle higher unbalanced currents than equivalent u ferrite cores due to 3X Bsat.
- Larger OD offers increased leakage L for DM attenuation since ferrite cores are typically larger than Nanocrystalline cores and require more turns of copper.

Nano Crystalline Advantages

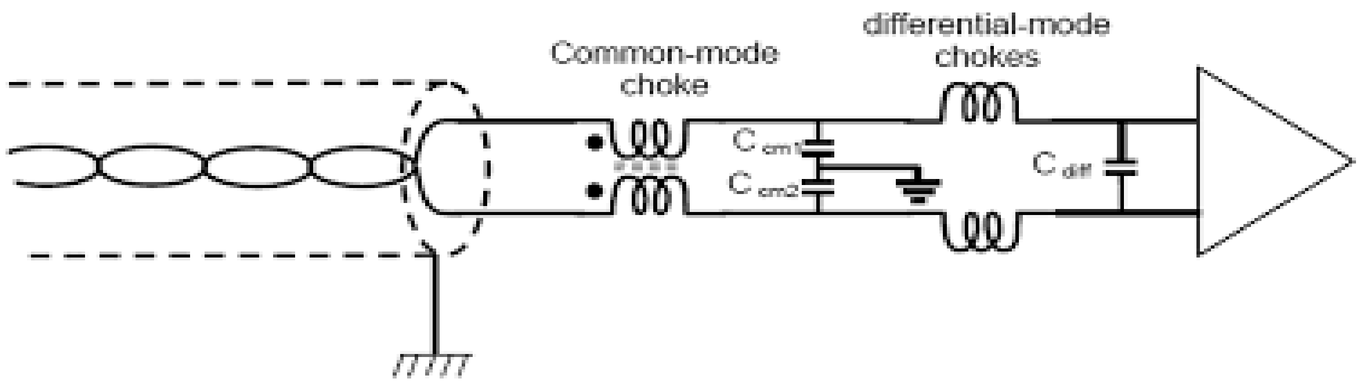
- Filter Order reduction (excellent low frequency and high frequency performance)
- Small size (reduced board space and volume)
- Low weight
- Thermal stability
- Energy efficiency (lower DCR)
- Mechanical Stability (no chip and crack issues)
- Ease of design (constant u over temp)

Differential Mode Inductor

The simplest differential mode inductor filter involves the placement of a single low permeability inductor in the line path and a capacitor between line and neutral. When High Frequency Noise tries to circulate through the system, it comes up against the high impedance of the differential mode inductor and therefore takes the low impedance path through the capacitor. The differential mode inductor effectively blocks the high frequency noise from moving through the system. Because the DM inductor is in the line path it sees the full line current (noise and DC offset) so it must be able to handle the peak power supply currents without saturating.

To prevent saturation, the DM inductor must be made with a core that has a low effective permeability that is typically gapped ferrite or powder cores. Some DM chokes are simply a few turns on a ferrite rod.

Some speculation that SiC construction may reduce magnetic coupling L di/dt which is primary source of differential mode noise.



X Capacitor

In most filter designs, you will find a single X capacitor which dampens differential mode noise between L and N. For high frequency energy the X capacitor acts as a short circuit.

Depending on the voltages applied, the capacitor may be designated X1, X2, or X3. Most applications will use an X2 capacitor.

Typical Values 47, 68 100nF

Since X Capacitors are placed “across-the-line”, there is not a danger of exposing a person to electric shock if they fail. They could cause a short circuit if shorted, so they must be designed to fail open.

Sub-class	Peak pulse voltage V_p in operation	Application	Peak values of surge voltage V_p (before endurance test)
X1	$2.5\ kV < V_p \leq 4.0\ kV$	High pulse application	$C_R \leq 1.0\ \mu F$: $V_p = 4.0\ kV$
			$C_R > 1.0\ \mu F$: (enter C_R in µF) $V_p = \frac{4}{\sqrt{C_R}}\ kV$
X2	$V_p \leq 2.5\ kV$	General purpose	$C_R \leq 1.0\ \mu F$: $V_p = 2.5\ kV$
			$C_R > 1.0\ \mu F$: (enter C_R in µF) $V_p = \frac{2.5}{\sqrt{C_R}}\ kV$
X3	$V_p \leq 1.2\ kV$	General purpose	No test

Y Capacitors

The Y capacitor dampens Common Mode Noise between the L/N and Protective Earth. For high frequency energy that comes simultaneously on both lines, the capacitor as a short circuit to ground.

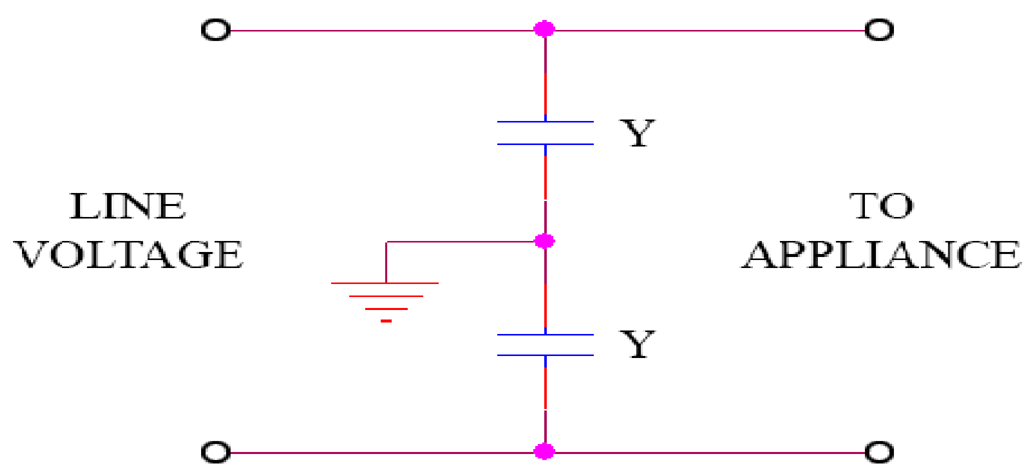
Y Caps must be safety approved

The capacitance value is limited because of the leakage current. The leakage current is mainly determined by the capacitance between line and ground. International equipment standards limit this current in most applications (250V, 60Hz) to <0.5mA

Typical values: 2.2nF, 470pF

Y class capacitors

Subgroup	Rated Voltage	Peak
	Test Voltage	
Y1	$\leq$ 500V	8 kV
Y2	150 $\leq$ V <300	5 kV
Y3	$\leq$ 250V	None
Y4	$\leq$ 150 V	2.5 kV



FCC Part 15 Radiated Emissions Limits

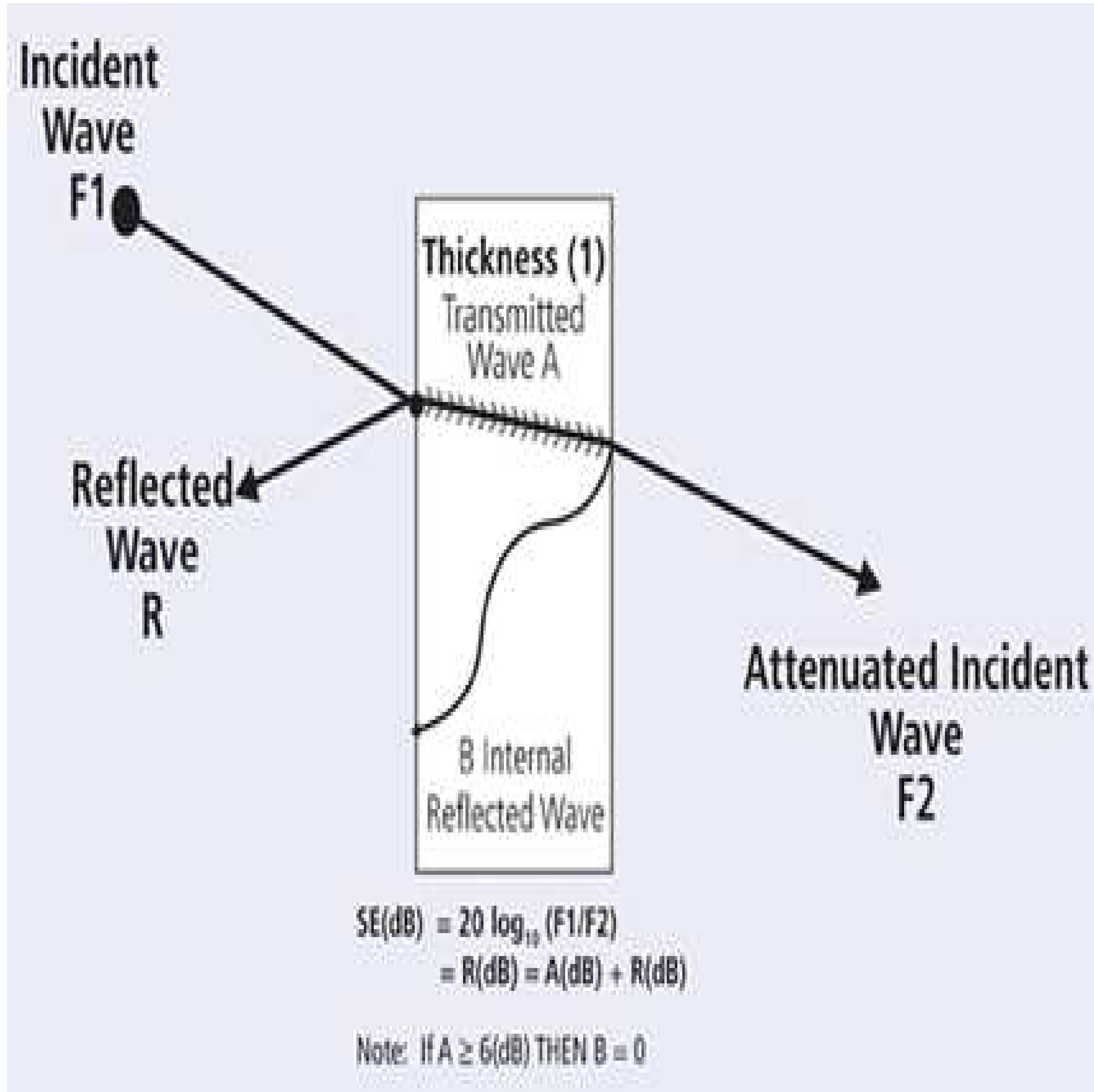
FCC Class B 3-Meter Radiated EMI Limit	
Frequency of Emission (MHz)	Field Strength Limit (µV/m)
30 - 88	100
88 - 216	150
216 - 1000	200
above 1000	200
FCC Class A 30-Meter Radiated EMI Limit	
Frequency of Emission (MHz)	Field Strength Limit (µV/m)
30 - 88	30
88 - 216	50
216 - 1000	70
above 1000	70

FCC conducted emission limits are specified for frequency ranges of 0.15-1.6 MHz and 1.6-30 MHz. While FCC radiated emission limits are specified for frequency ranges of 30-88 MHz, 88-216 MHz, and 216-1000 MHz at a fixed measuring distance of 3 meters. These limits apply to both systems with SMPS installed and SMPS in stand-alone applications.

Shielding Definitions

Shielding is a conductive barrier enveloping an electrical circuit to provide isolation. The "ideal" shield would be a continuous conductive box of sufficient thickness, with no openings. Shielding deals with radiated and absorbed energy.

Shielding Effectiveness (SE) is the ratio of the RF energy on one side of the shield to the RF energy on the other side of the shield expressed in decibels (dB).



Shielding Calculations

For sources outside of the shield, the absorption and reflection of the shielding material, in dB, are added to obtain the overall SE of the shield. For sources within the shield, roughly only the absorption of the shield can be considered.

The absorption of the shielding material at frequencies of concern is controlled by:

- Conductivity
- Permeability
- Thickness

The reflectivity of the material at the frequencies of concern is controlled by.

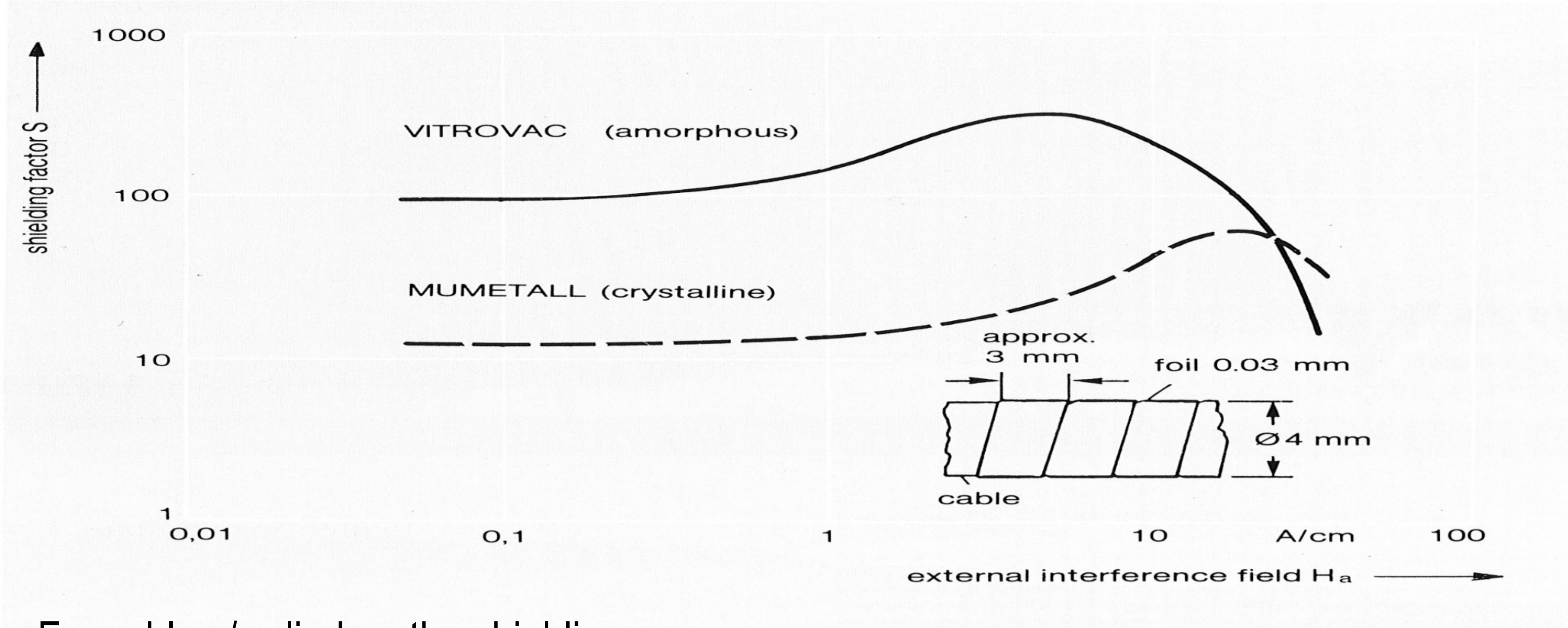
- Conductivity
- Permeability

For both Absorption and Reflectivity the active frequency plays a major role in the selection of the required shielding material.

However, this is only true for our “ideal” shield. Two other major factors are:
“Apertures” – holes or slots in the enclosure.

The mechanical characteristics and effectiveness of the gaskets used on the enclosure.

Shielding of wire made of crystalline versus amorphous material



For cables / cylinders the shielding formula is:

S=H(a)/H(i)=d/D*u(r)+1

H_a: external field to be shielded off
H_i: residual field in the interior of the shielding
d: average diameter in direction of the lines of flux
D: wall thickness
μ_r: relative permeability, mostly μ_4

Higher shielding factor through amorphous material because of:

- Higher permeability
- Insensitiveness against mechanical deformation
- Higher electrical resistivity (especially for high frequency shielding's

Shielding of equipment/instruments made of crystalline versus amorphous material

	80% Nickel Iron*	Amorphous shielding foils**
Magnetic properties	μ_4 > 150.000	μ_4 >100.000
Mechanical properties	From hard to deep draw quality	Only “hard” condition
Forms of supply	Bar, rod, plate, strip, foil	Only foils

For most external / irregular shaped shielding, NiFe is the material of choice.

Formula for thin-walled spherical closed shell:

$$S = \frac{H_a}{H_i} = \frac{4}{3} * \frac{d}{D} * \mu_r + 1$$

Shielding cans for display instruments

*: according ASTM 753; typical values VACOPERM 100
**: Cobalt based amorphous material; typical values VITROVAC6025

Wolman frequency and Skin Effect

Wolman frequency defines the frequency at which half the shielding is penetrated by the magnetic field.

The higher the Wolman frequency rating the more effective the shielding is against higher frequency.

Typically for high frequency design the Wolman frequency dictates the material, thickness and number of layers to be specified.

At frequencies (typically > 1kHz) there is also skin affect caused by eddy currents induced in the magnetic shield. Skin effect helps define the Wolman frequency parameter.

$$fw = \frac{4 * \rho}{\pi * \mu_0 * \mu_i * d^2}$$

$$\delta_{skin} = \sqrt[2]{\frac{\rho}{\pi * f * \mu_0 * \mu_i}}$$

ρ: electrical resistivity
μ_0: permeability constant
μ_i: initial permeability
f: frequency
δ: skin depth

material	Electrical resistivity $\Omega mm^2/m$	Initial permeability μ_i	Thickness d mm	Wolman frequency f_w kHz
80%NiFe*	0.60	100.000	0.10	6.1
Amorphous material	1.15	150.000	0.023	17

Laminated shielding material

Nanocrystalline material offers advantages for laminated shielding applications for applications such as wireless charging due to the higher u across the frequency range.

Ferrite material has a defined cutoff frequency and exhibits a 1/f dependence above this frequency.