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1 Which input power do I need to apply to create a certain electrical field strength inside the TEM cell?

The E-field (V/m) between septum and lower (upper) wall of the TEM Cell is

E = V/d where V is the RMS voltage of the applied signal and d is the distance between septum and lower (upper) wall. This is based on the simplified assumption that the E field would be perfectly homogenous/evenly distributed.

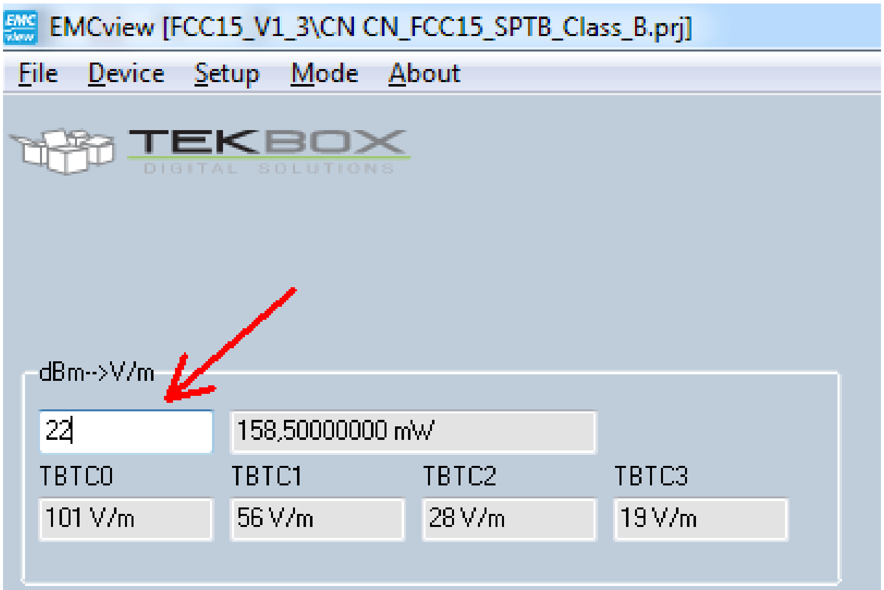
A more accurate formula is E = V*Cor/d where Cor is a correction factor for the average field strength over the volume of the DUT derived from the analysis of the field distribution over the cross section of the cell.

Assuming the DUT is placed in the center of the cell and in the middle between bottom wall and septum, we can however use the simplified formula with sufficient accuracy.

TBTC0	d = 2.8 cm	$E = (\sqrt{P \cdot 50\Omega}) \cdot 35.7$
TBTC1	d = 5 cm	$E = (\sqrt{P \cdot 50\Omega}) \cdot 20$
TBTC2	d = 10 cm	$E = (\sqrt{P \cdot 50\Omega}) \cdot 10$
TBTC3	d = 15 cm	$E = (\sqrt{P \cdot 50\Omega}) \cdot 6.66$

Alternatively you can download and install a copy of EMCview, which gives you access to many features without requiring a license:
https://www.tekbox.com/product/emcview-pc-software-emc-compliance-testing/

Open menu **MODE**, **GENERATOR** and you will find a dBm to V/m conversion utility in the upper left corner of the window.
Upon entering a power level in dBm, the utility will calculate the resulting electrical field strength for all Tekbox Open TEM-Cell models. The screenshot below shows the electric field strength that can be achieved by driving the TEM cells with a Tekbox TBMDA1 modulated amplifier. The lower the septum height, the higher the resulting field strength for any given power level:



Tekbox currently offers four dedicated modulated wideband power amplifiers to drive the TEM-Cells. You don´t need to have a dedicated RF signal generator to drive these amplifiers. They are designed to deliver their respective maximum output power with ≤ 0dBm input power and have built in modulating capability. Consequently they are suitable to be driven by the tracking generator signal of a spectrum analyzer.

Amplifier model	frequency range [MHz]	Max. output power [dBm]	Max. el. field strength TBTC0 [V/m]	Max. el. field strength TBTC1 [V/m]	Max. el. field strength TBTC2 [V/m]	Max. el. field strength TBTC3 [V/m]
TBMDA1	40 - 3500	22	101	56	28	19
TBMDA2	10 - 1500	27	179	100	50	33
TBMDA3	10 - 1000	37	565	317	158	106
TBMDA4	0.1 - 50	37	565	317	158	106

2 What is the useful frequency range of a TEM-Cell?

The datasheet of the TEM-cells specifies values for S11 and S21 of the TEM-cells.

S21 is the insertion loss over frequency and measured by feeding a RF signal into one port and measuring the output signal at the opposite port. It basically characterizes how much a signal is attenuated, once it is picked up by the septum. However, two things need to be considered – the insertion loss is measured with an empty TEM-cell and the signal is not picked up at the far side and travels all the way to the other side. Means, the geometry of the DUT will have a certain impact, which is difficult to characterize unless the DUT is small compared to the septum height and the signal is picked up by the entire area of the septum. In practice, independent of the 3dB frequency of S21, any Tekbox TEM cell can pick up radiated emissions well up to 6 GHz or above. However, when converting the measurement result into a corresponding far-field value using the method specified in the IEC 61000-4-20 standard, the accuracy of the conversion degrades above the 3dB frequency of the TEM cell.

S11 characterizes the input reflections, when a RF signal is fed into one port and the other port is terminated with 50 Ohm. At lower frequencies, only the principal wave (TEM mode) propagates and the E-field distribution inside the TEM-cell is uniform. Due to the geometry of TEM cells, resonances at higher frequencies cannot be avoided. S11 deteriorates and higher order TEM- modes develop. Means the E-field is not uniform anymore and the higher the frequency, the more minima and maxima can be observed. The formula for field strength and the IEC 61000-4-20 conversion loses accuracy. Our measurements have shown, that the field is reasonably uniform up to a S11 of -15 dB and a DUT cross section ≤ 1/5 of the cross section of the TEM cell. For more details, you can google for the papers of Myron L. Crawford, the inventor of the TEM cell: *generation of standard EM fields using TEM transmission cells*

The brute force "Tekbox torture method" for immunity testing can be applied up into the several GHz range, without too much concern about the DUT volume or S11. Refer to chapter 8.

3 How do TEM-cells compare to near-field probes or antennas

If you only have a hammer, everything looks like a nail. This also applies, if you just have a set of near-field probes, or just a TEM-cell or a measurement antenna. I don´t need to mention that you will be happier, if your drawer is filled with various tools.

Near-field probes

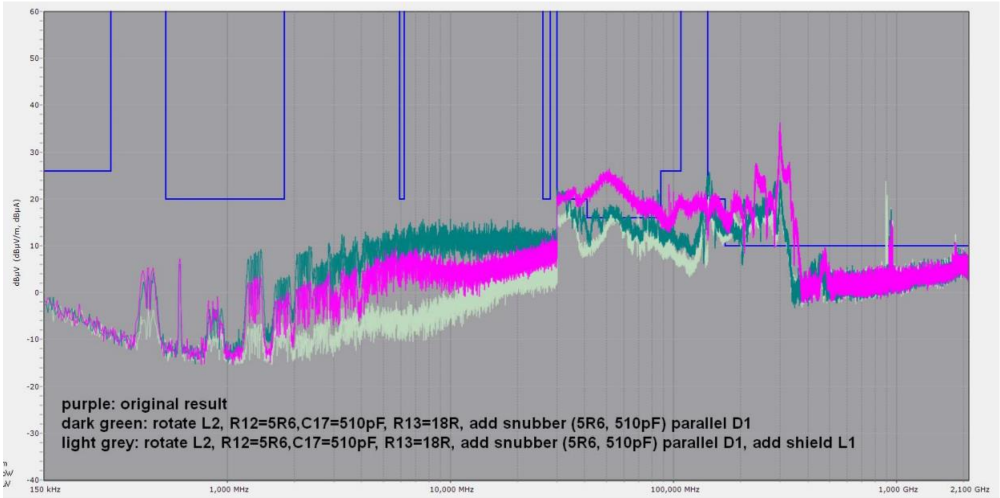
Near-field probes are an essential tool to locate sources of radiated emissions on a PCBA. Tekbox near-field probes are not only specified with respect to coupling loss versus frequency, but also with respect to converting the measurement results into magnetic and electric field strength. Furthermore, trans-impedance tables of the H-Field probes enable converting measurement results into corresponding RF currents on PCB traces. As near-field probes are designed to give a good special resolution, which is necessary to clearly locate the origin of radiations, they only show the radiations of a small area of the PCB. In order to get a full picture, it is necessary to manually scan across the PCBA. You can compare it with observing the starry sky through a telescope.

Another advantage is the probes insensitivity to ambient noise. Whatever you see on your spectrum analyzer is radiated from your DUT.
Near-field probes are equally useful for debugging immunity issues. Feeding the probes with an RF signal makes it easy to locate susceptible areas on PCBAs.
There is sometimes a misconception that the signals picked up by near-field probes can be converted into an equivalent far field value, replacing an antenna measurement. Without going into details – there is a reason why there are antennas and there is a reason why there are near field probes. As you will see, there is also a reason why there are TEM-cells.

TEM-cell

TEM-cells were initially designed to generate strong and well defined E-fields for immunity testing. The necessary RF power required to achieve the E-field levels specified in various EMC standards are much lower, if you use a TEM-cell than if you use an antenna. As shown in chapter 1, you can produce an E-field with nearly 600V/m using a cheap 5 W RF amplifier and a TBTC0. If you have the budget to buy a Ferrari, you could instead buy the RF wideband amplifier necessary to create the same field strength in the far field of an antenna. This may be a bit exaggerated, but it is not very far from truth. In fact, in order to cover the entire frequency range specified in your standard, you most likely need more than just one amplifier.
On the downside, the dimensions of TEM-cells cause limitations to the size of the DUT that you can accommodate.

With respect to radiated emission testing, TEM-cells are very wideband. You can pick up signals from well below 100 kHz up to 6 GHz and above. TEM-cells measure in the near field and provide some attenuation to ambient noise, so you will be able to see emissions, which would require a shielded environment and pre-amplifiers in case of using an antenna. On the downside, TEM-cells deliver near field values that cannot simply be converted to an equivalent far field result, by just adding some offset. Nevertheless, there are correlation methods such as specified in IEC 61000-4-20, however they require some additional effort and have some limitations.
Besides being very efficient in getting a good overview about the entire spectrum radiated from a DUT, TEM-cells excel when using it to monitor the effect of hardware modifications / optimizations of a DUT. The TEM-cell is relatively insensitive with respect to the placement of the DUT, which makes it easy to track relative changes of the radiated emission levels. If your DUT exceeded the limits say 10 dB in the test house, measure it in the TEM cell and optimize the design until the level measured in the TEM cell shows at least 10 dB improvement. You can use Tekbox EMCview, save the graph of every iteration step, overlay it and have a perfect documentation of your efforts. A TEM cell is very convenient to use, as it can be easily accommodated on any lab desk.



Example: using a TEM-cell and EMCview software to track the effects of hardware modifications over a wide frequency range

What is left to mention is CISPR 25 and CISPR 14 specify radiated emission levels for TEM-cells as an alternative to far field limits. In this case, you can directly apply the levels measured at the output of the TEM-cell and don´t need to convert it. There are some limitations though. CISPR 14 restricts TEM-cell measurements to battery powered equipment.

Measurement antenna

The difference between an antenna and a measurement antenna is the availability of antenna factor tables. Antenna factors are usually given in dB/m. Adding the antenna factor to the output signal of your antenna in dBµV results in the corresponding electrical field strength in dBµV/m.
Most standards specify radiated emission levels along with a defined spacing between DUT and antenna.

CISPR 16 defines various frequency bands and the corresponding antennas:

<table>
<tr><th>Frequency range</th><th colspan="2">Antenna type</th></tr>
<tr><td>Up to 30 MHz</td><td colspan="2">Predominantly loop antennas</td></tr>
<tr><td>30 MHz – 200 MHz</td><td>Biconical antenna</td><td rowspan="2">Hybrid antennas</td></tr>
<tr><td>200 MHz – 1 GHz</td><td>Logarithmic periodic antenna</td></tr>
<tr><td>Above 1 GHz</td><td colspan="2">Horn antenna</td></tr>
</table>

Using measurement antennas gives you results that can be directly compared against standardized radiated emission levels.
In practice, there are quite a few obstacles as long as you don´t have an anechoic chamber at your disposal. Radiated emission measurements using antennas in an unshielded environment are hampered by ambient noise. In fact, it is not trivial to distinguish ambient noise from the emissions of your DUT. The standard method of turning on/off the DUT and comparing the two spectra may have been appropriate years ago. However, nowadays the ambient noise spectrum is highly dynamic, rendering this method pretty useless. This is where a TEM cell comes handy. Get an overview of your DUT´s spectrum using a TEM-cell first and next measure the corresponding far field levels with an antenna.
Where to set up the antenna? Setting it up inside the lab may cause significant errors due to reflections. If possible, set up the measurement on a flat roof or any other open space environment.
Another obstacle is caused by antenna gain limitations. Measurement antennas are wideband and consequently don´t have high gain. The lower the gain, the higher the antenna factor. As mentioned before, the antenna factor has to be added to the measurement result. This means that the base noise level of the spectrum analyzer is offset by the antenna factor and in case of standards with low limit levels, the base noise corrected with the antenna factor may come very close to the limits or even exceed the limits. This is no big deal in anechoic chambers. The lack of gain is compensated using low noise pre-amplifiers. However in an unshielded environment, ambient noise is likely to cause nonlinear distortions, if pre-amplifiers are inserted between antenna and spectrum analyzer. As a workaround for unshielded environment, the antenna distance can be decreased. In case of CW emissions, it is also appropriate to reduce the measurement bandwidth in order to reduce the base noise.

Summary

Pre-compliance radiated noise testing:

If you don´t have access to an anechoic chamber, combined use of a TEM-cell, near field probes and measurement antennas are the way to work around.
Start with a TEM-cell to identify critical emissions. If appropriate, use a suitable and documented reference device or IEC 61000-4-20 to correlate the levels with far field measurements.
Next set up your DUT in a free space environment and use a measurement antenna to obtain the far field levels of any emission considered critical based on the TEM cell results.

In case that any of the emissions exceed the corresponding limits, use near field probes to locate the origin of the emissions, which will point you to the root cause.
Iteratively optimize the DUT hardware, using the TEM cell to monitor relative improvements.
Once you are confident that your improvement sufficiently reduced the emissions, validate it using the measurement antenna.

Pre-compliance radiated immunity testing:

Use TEM-cells. Unless you don´t have a generous budget, don´t even think about antennas. Far field set ups require high power RF wideband amplifiers.

4 Open TEM-cells versus closed TEM-cells

An open TEM-cell does not have any side walls. A closed TEM-cell has metal side walls. A shielded door at the side provides access to insert the DUT. The door may be equipped with a shielded glass window to observe the DUT. The DUT is electrically connected via feed through filters.

The only advantage of a closed TEM-cell is shielding the septum from ambient noise. However the constructive details cause closed TEM-cells being significantly more expensive than open TEM-cells. The maximum size of the DUT is limited by the dimensions of the shielded door. Handling of the DUT is easier in case of an open TEM-cell. Unless you have a closed TEM-cell with a shielded window, immunity testing may be handicapped as indicator lamps, LEDs or displays cannot be observed.

A closed TEM-cell can be substituted by placing an open TEM-cell inside a shielded tent or shielded bag. The combined cost of a shielded tent + open TEM-cell is lower than the cost of a closed TEM-cell. Furthermore, a shielded tent or shielded bag can be used for other purposes, such as protecting a conducted noise measurement set up from ambient noise.

5 TEM-cells versus GTEM-cells

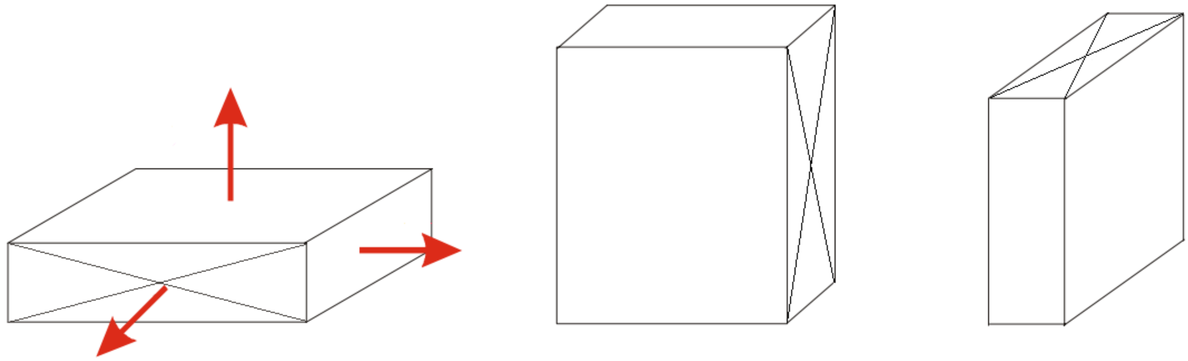
GTEM-cells are pyramidal shaped 50-ohm transmission lines. A 50-ohm coaxial input is transformed to a rectangular cross section with an aspect ratio of 3:2 height to width. The septum is typically connected to an N-connector at the input side and terminated with a distributed 50 Ohm resistor at the opposite side. The volume field is terminated in a RF absorber. GTEM-cells can be designed to operate well into the GHz range, even at large size. However they may have limitations at lower frequencies due to the absorption limitations of RF absorber foams below 1 GHz.
GTEM-cells have their septum elevated with respect to the vertical center, offering more space for DUTs. Consequently, IEC 61000-4-20 correlation can be applied to larger DUTs as compared to TEM-cells.
GTEM-cells are excellent instruments to carry out radiated noise and immunity testing, however their size and cost may exceed the constraints of pre-compliance budgets.

6 How to correlate (G)TEM-cell measurements with far field limits

There is a common misconception, that the output level of the (G)TEM-cell can be converted into an equivalent antenna measurement result, by simply adding a correction curve.
The amplitude of the emissions measured at the output of the (G)TEM cell is rather insensitive with respect to the shifting the placement of the DUT within the TEM cell. The DUT can be shifted across the bottom plate of the (G)TEM cell and the amplitude will remain pretty constant. This is of great advantage when

repeatedly removing and re-inserting the DUT during HW optimization. In order to track relative changes of the emissions, it is not necessary to accurately place the DUT in the same position for every measurement. However, the amplitude of the emissions measured at the output of the TEM cell are not constant with respect to the orientation of the DUT. In order to avoid confusing orientation with placement - orientation means whether the DUT is position is upside down, rotated 90°, etc.:

3 main orthogonal orientations of the DUT:



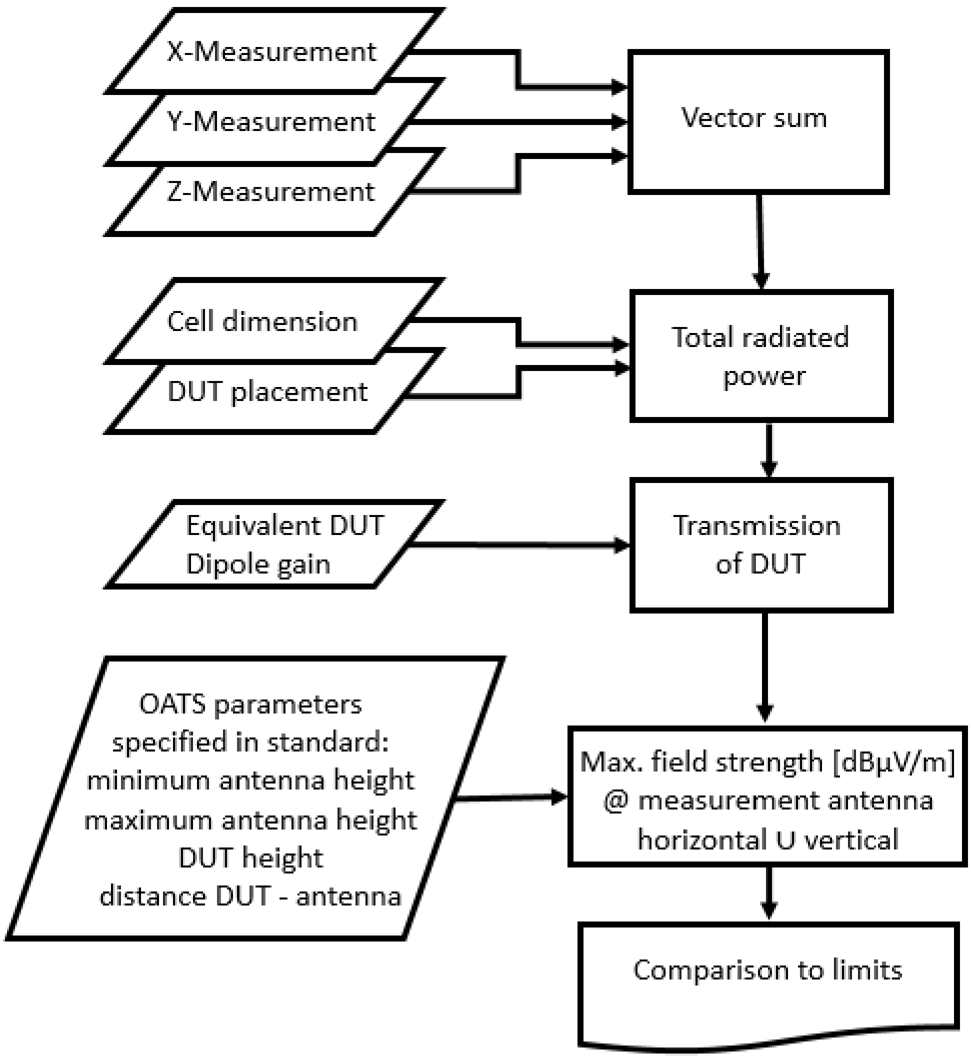
So, whenever attempting to correlate the measurement result, it is necessary to find the DUT orientation, which yields the highest emission levels. There is not necessarily just one single, “worst” orientation. A DUT typically would radiate at various frequencies, originating from different building blocks of the DUT. Consequently, the worst case orientation may not be the same for different spurious.

Assuming you take the effort to find the worst case DUT orientation, there are several approaches to figuring out, if any spurious emissions measured with the TEM cell would pass or fail the radiated emission limits.

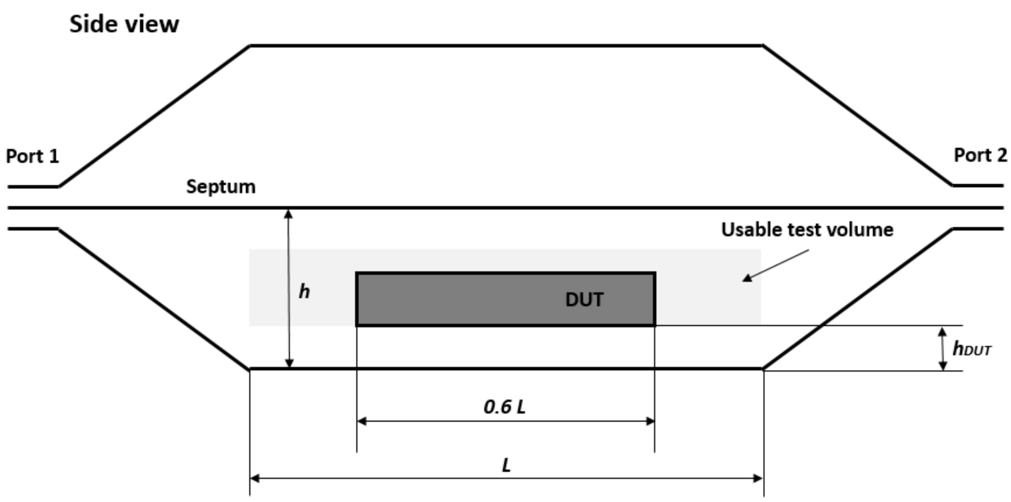
1) Purely empirical and extremely ballpark: any emission level of 40 dBµV or more could be considered as critical. Consider that limits are different for different frequencies and standards.
2) Again empirical and ballpark: TEM cell levels in dBµV are often within ± 10 dB of the equivalent far field level in dBµV/m in 3 meter distance.
3) Use a product of similar dimensions, which was already tested in an anechoic chamber as a reference device
4) Use the correlation method specified in IEC 61000-4-20
5) Use a combined approach based on TEM-cell, near field probes and antenna measurements as outlined in the summary of chapter 4.
6) You do not need to carry out a correlation for a few standards, as they alternatively offer limits for TEM-cells (e.g. CISPR 14, CISPR 25)

IEC 61000-4-20 correlation

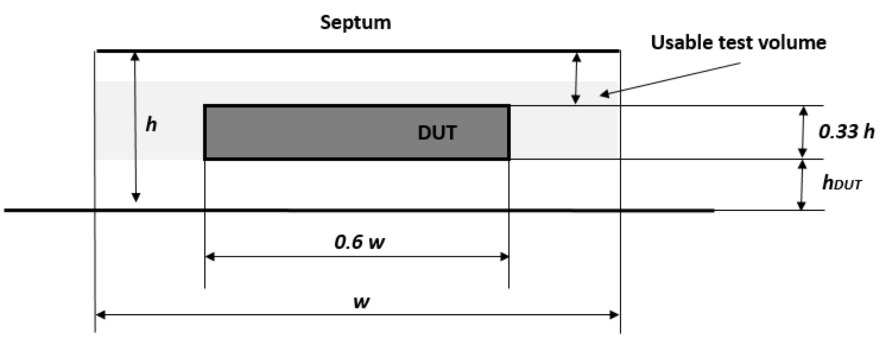
The standard describes several methods, which basically differ in how many orientations of the DUT are measured in order to calculate the vector sum of the radiated emissions.
The method described here below describes the so called “three position correlation algorithm”. It requires measurements of the three main orthogonal DUT orientations. The main simplifying assumption in this algorithm is that the radiating structures of the DUT have no greater gain than a dipole and a dipole radiating pattern. The output of the algorithm measurements are then converted into an equivalent far field value. The algorithm is typically applied for frequencies above 30 MHz.



According to IEC 61000-4-20, following requirements with respect to DUT size and placement in relation to the dimensions of the TEM cell need to be fulfilled in order to achieve acceptable accuracy:



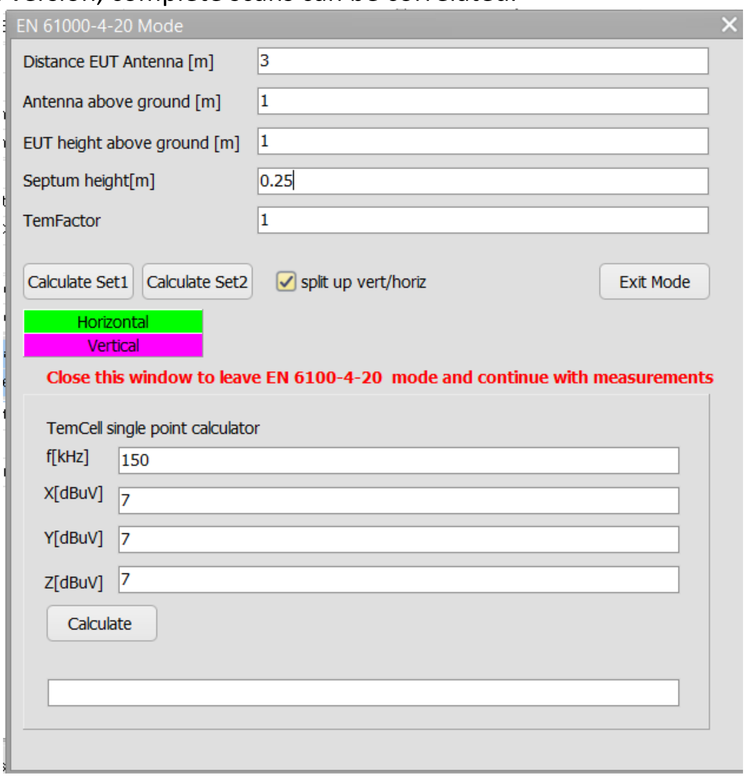
Cross sectional view



When rotating the DUT into any of the three main orthogonal positions, the geometrical center of the electronic section of the device shall remain in the same position.

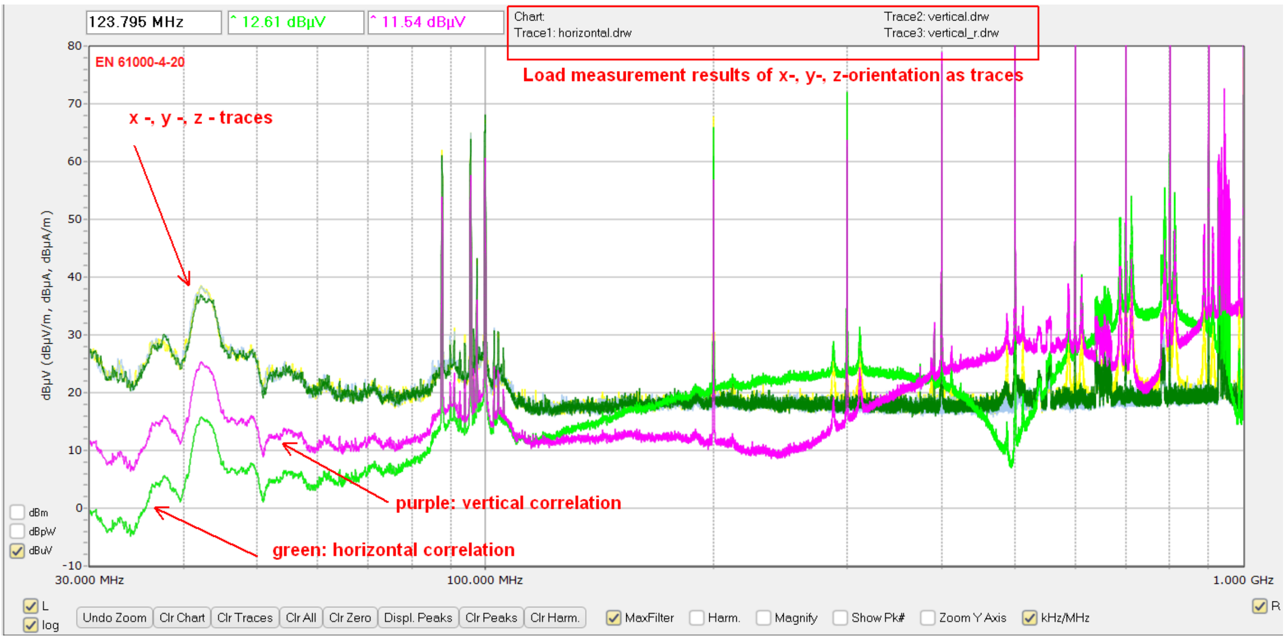
With EMCview V7.06, Tekbox introduced an implementation of the three position correlation algorithm. EMCview can be downloaded at
https://www.tekbox.com/product/emcview-pc-software-emc-compliance-testing/

The algorithm can also be used to calculate the correlation at discrete frequencies without software license. In the licensed version, complete scans can be correlated.

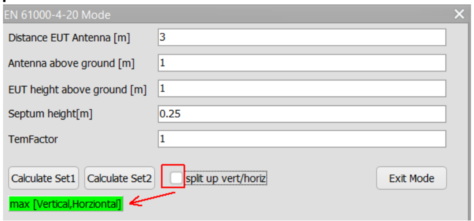


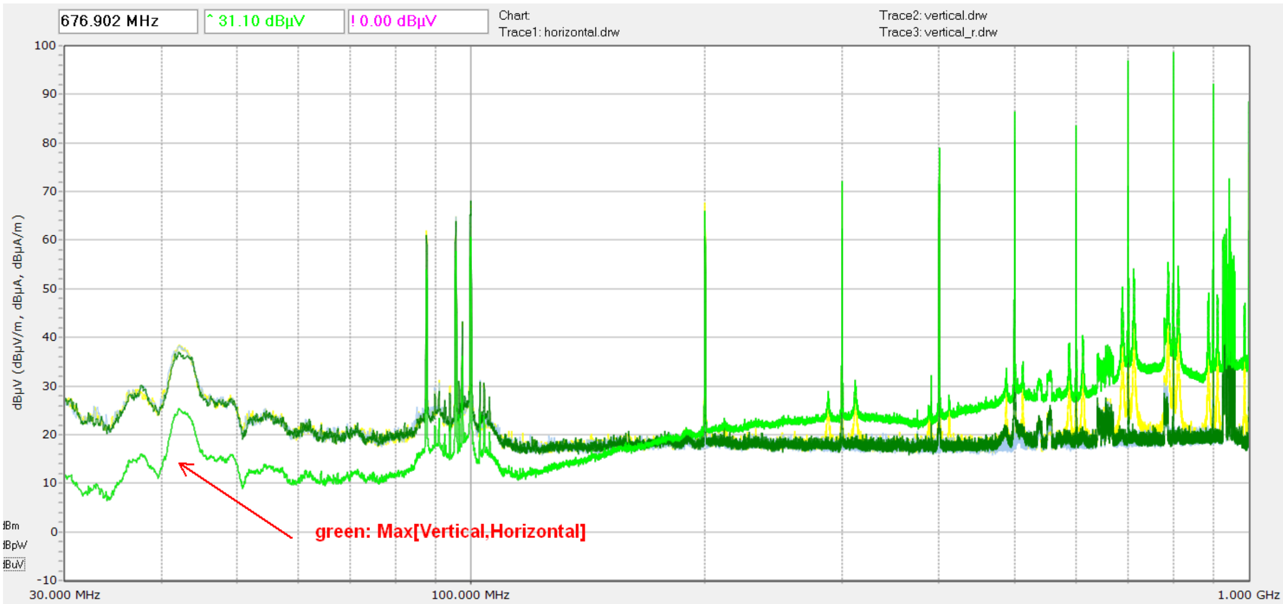
Start the correlation tool by clicking the EN61000-4-20 and CALCULATE buttons. In the pop up window, enter the test site parameters according to standard and the septum height of the respective TEM-cell. The TEM-factor is by default "1". You can modify it in order to fine tune / match the result, in case that your DUT was already measured in a test house.

In order to correlate an emission measurement at a single frequency, simply enter the spurious amplitudes in dBµV for the three main orthogonal orientations and click the calculate button.
In order to correlate a scan, carry out the scan for the three main orthogonal orientations one by one and save the resulting graph using the SAVE CHART feature after every measurement. Next load the three graphs as TRACES and click the CALCULATE SET1 button. The resulting correlation will be displayed as additional graph in the graph window and can be processed like any other measurement graph (peak search, labeling, test report creation, etc.)



The “maximum correlation” calculates (sqrt(vert^2+hor^2). This can be used as kind of a worst case, without looking into whether an emission problem occurs in horizontal or vertical direction.





7 How to carry out pre-compliance radiated emission testing with open TEM cells?

Refer to chapter 4 and 6 of this document.
For more details on the combined approach using TEM-cell, near-field probes and antennas, refer to our application note *AN_ pre_compliance_radiated_noise_measurements.*

8 How to carry out pre-compliance radiated immunity testing with open TEM cells?

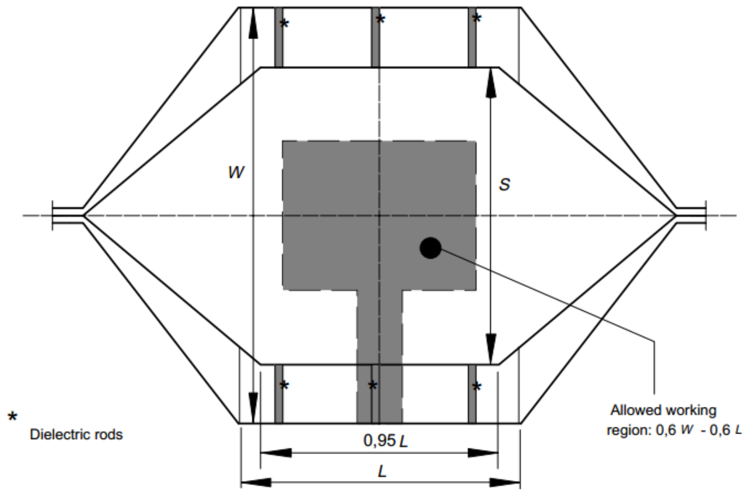
The respective standard that needs to be applied to your product specifies the frequency range and electrical field strength that has to be set up for the immunity test. If you want to carry out the test as standard conformant as possible, you have to ensure that your DUT fits into the usable working volume as specified in IEC 61000-4-20 and shown in chapter 6. Calculate the required RF power according to chapter 1 in order to achieve the desired field strength. Then run 3 sweeps, to cover the 3 main orthogonal orientations of the DUT in order to find the most sensitive orientation, if any.
Most susceptibility issues are caused by PCB traces acting as an antenna and feeding RF to semiconductor junctions. RF gets rectified at semiconductor junctions, creating bias offsets, which ultimately may cause malfunction of the DUT.
You can expect maximum susceptibility with the DUT orientation such that PCB traces are in parallel to the electric field vector. The electric field is orthogonal to the septum. A PCB in parallel to the septum is not subject to a strong gradient of the electric field and susceptibility issues are far less likely.

Be aware that setting up and carrying out a test as accurately and close to the standard as possible, will make your task eventually unnecessary time consuming and eventually. By the end of the day, the target of your immunity testing is to ensure maximum immunity of the product and not just passing the immunity test in the test house. You may put much detail into ensuring that the electrical field is set up to exactly 10V/m across the entire specified frequency range, pass the test, but somewhere in the field unpleasant failures happen, because an unanticipated use case exposes your product to a higher field strength. You may oversee a weak point in the design, because the failure mode happens at slightly above 10V/m. This might be fixed as simply as by adding a tiny, inexpensive capacitor and give you immunity up to several hundred Volt per meter.
The “Tekbox torture method” addresses this subject with brute force. Inject the maximum RF power that you can generate into the smallest TEM-cell that you have. At Tekbox, we prefer using the TBTC0 and driving it with 5W, which results in a field strength of nearly 600V/m. Since most DUTs wouldn´t fit into it, we remove the housings to expose the PCBA. If the PCBA is still too large, we test it in sections or use the next larger TEM-cell that can accommodate it. This test can be set up within minutes and we don´t need to do repetitive sweeps in order to find the most sensitive orientation. If the design has a weak spot, we will find it irrespective of the orientation.
Have a look at the application note *AN_Immunity_testing-_Tekbox_TEM_Cell*, which shows an example on how to succeed with the Tekbox torture method.

9 What is the usable volume of Tekbox TEM Cells?

The dimensions of all Tekbox TEM-cells are documented in the datasheet.
In general you can place anything into the TEM-cell, as long as it fits in between bottom plate and septum. You may even remove spacers in order to get better access to the interior of the TEM-cell. If you have a DUT which is larger than the TEM cell, you may measure it section-wise. It is perfectly legitimate to use the entire volume of the TEM-cell, as long as you are aware of how it will affect your measurement. In case of

relative radiated noise measurements or brute force immunity testing, you will achieve your goals without bothering the usable volume.
If you want to carry out your measurement as standard conformant as possible, refer to ISO 61000-4-20. The standard specifies the useful volume in relation to the dimensions of the TEM cell. The corresponding drawings are shown in chapter 6 of this document.
If you make radiated noise measurements according to standard CISPR25, you will also find a specification for the usable volume or allowed working region, as they call it.

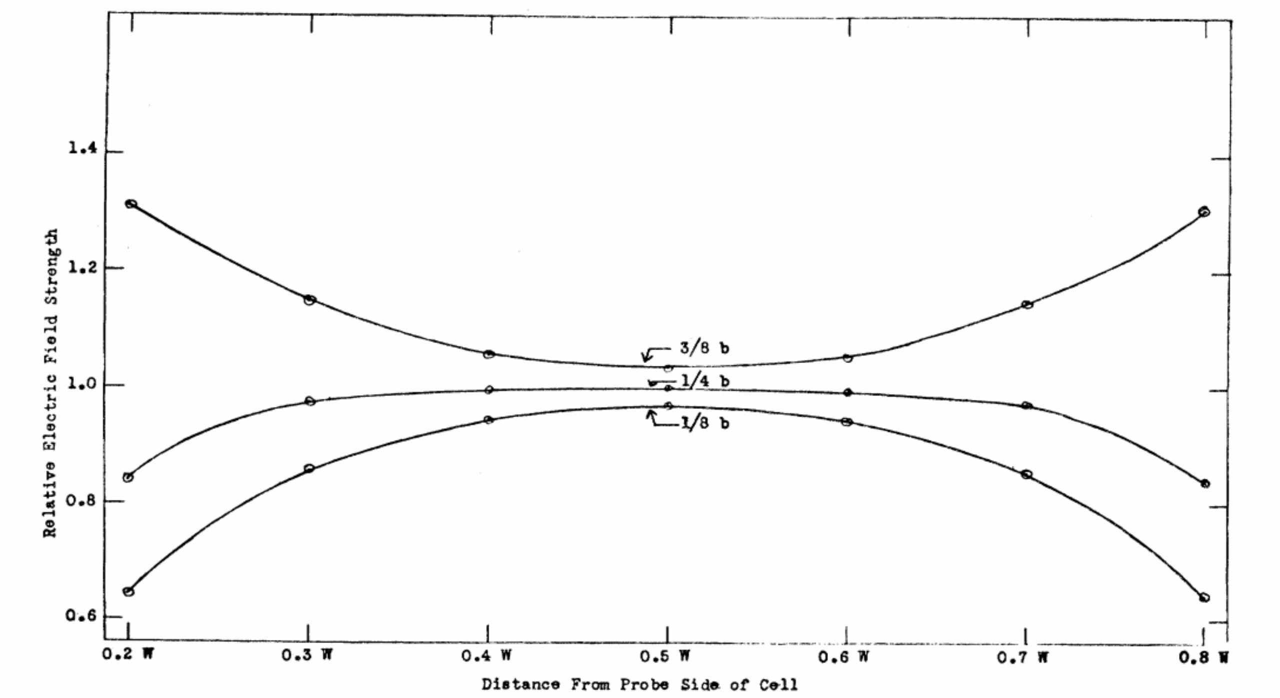


allowed working region – screenshot taken from CISPR25, Annex E

10 Field distribution in a TEM-cell

The paper *Generation of Standard EM Fields Using TEM Transmission Cells* from Myron l. Crawford, the inventor of the TEM cell, published in IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY, VOL. EMC-16, NO. 4, NOVEMBER 1974 is an excellent reference with respect to the field distribution in TEM cells.

The drawing below illustrates the field distribution over the cross section of a TEM cell with a form factor very similar to the Tekbox TEM cells.



Relative electric field distribution inside cell. Cross sectional cut

W: width of the TEM cell top/bottom plate

b: inner height of the TEM cell (septum is at height b/2)

Measurements of the field distribution of the Tekbox TEM cells, carried out in the frequency range with S11 ≤ -20 dB were closely corresponding with the above drawing.

11 History

Version	Date	Author	Changes
V 1.0	3.9.2016	Mayerhofer	Creation of the document
V 1.1	3.3.2021	Mayerhofer	Update of all chapters
V 1.2	10.8.2023	Mayerhofer	Update of chapter 6