LANGER
EMV-Technik

IC TEST SYSTEM

User manual
Probe set

RF power field coupling 1 GHz
P1401 / P1501 set

Magnetic field:
P1401

Electric field:
P1501

Supplied from RF power amplifier

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1 RF field sources for electric field and magnetic field

The ***P1401*** and ***P1501*** probes are field sources. They are used to generate electric (E) or magnetic (H, B) RF fields. The field sources allow the user to couple defined and reproducible RF fields into IC housings. The field sources can only be operated in conjunction with a power amplifier.

The RF field sources are used in the context of determining the RF immunity of electronic systems in tests according to the standard IEC (EN) 61000-4-3. RF power is coupled into the electronic systems during these tests using different methods. RF current is coupled to the cable harness via a current transformer by the BCI method (*Bulk Current Injection*), for example. RF radiation can also be coupled to an electronic system via a TEM cell, stripline or antenna in shielded rooms.

The EMC standard for ICs (IEC 62132) describes three typical measuring methods for the EMC characterisation of ICs: the DPI (Direct Power Injection) method, the TEM cell (Transverse Electromagnetic Cell) method and the use of an IC stripline.

All of these methods generate electric and magnetic RF fields on the printed circuit boards of electronic systems. These fields act on the surface of the printed circuit board and also penetrate the housings of ICs, resulting in the generation of disturbances in the ICs. Apart from conductive RF power coupling via the DPI method[1] (IEC 62132), inductive and capacitive coupling due to magnetic and electric fields are important mechanism of interference with ICs. It is usually either an electric or a magnetic field which interferes with an IC in an electric system. The IC's weak point usually responds to only one type of field.

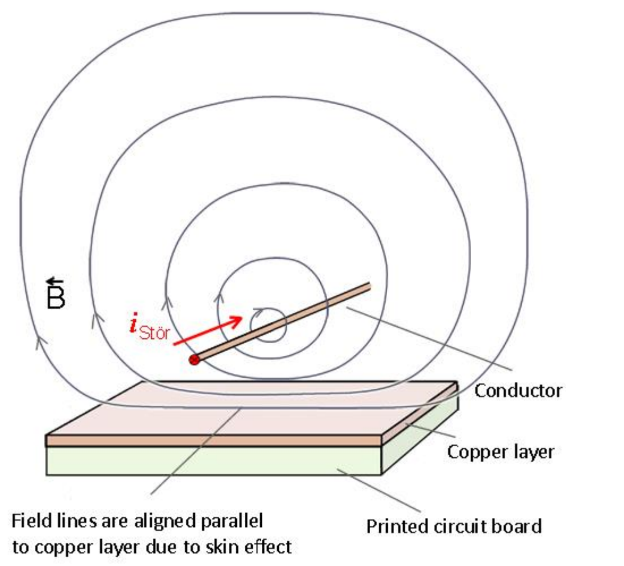
The ***P1401*** field source generates a magnetic RF (power) field and the ***P1501*** field source generates an electric RF power field.

The ***P1401*** field source can be used to clearly identify weak points of the test IC that respond to magnetic RF fields and the ***P1501*** field source allows the clear identification of weak points in terms of electric RF fields. Fault mechanisms that occur during these tests can be clarified by monitoring the test IC which includes the measurement of fault processes on IC pins with an oscilloscope or the analysis of the IC's internal error registers, for example. These tests are the basis for the development of ICs in compliance with EMC requirements.

The field source dimensions depend on how RF fields are coupled to ICs. The design of the field sources is based on the respective field orientation (**Figure 1, Figure 2**).

The shape of the RF fields in the IC's assembly area on the electronic module is decisive in this respect. The assembly area is the space where the test IC can be arranged on the surface of the printed circuit board. The field in this assembly area is mainly determined by the inner metallic structure (layout) of the printed circuit board. Printed circuit boards usually contain continuous copper layers which shape the fields.

[1] Conducted EFT/Burst tests on ICs are carried out with the ***P500*** probe family (***Probe set for RF power coupling analysis***) from Langer EMV-Technik GmbH



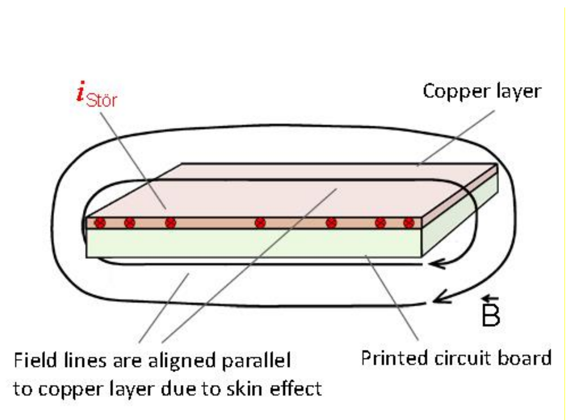


Figure 1 Magnetic field development on printed circuit boards: the RF current $i_{Stör}$ flows through the conductor beside the printed circuit board and generates a magnetic field B. The copper layer aligns the field parallel to the board's surface in the assembly area.

Figure 2 Magnetic field development on printed circuit boards: the RF current $i_{Stör}$ flows through the printed circuit board and generates a magnetic field B. The metal layer (copper layer) aligns the field parallel to the board's surface in the assembly area.

Magnetic fields are aligned parallel to the printed circuit board due to the flux displacement effect (the field is cancelled due to eddy-current fields) (**Figure 1** and **Figure 2**). These directional fields affect the ICs in the assembly area. The field lines are parallel to the IC housing. The field sources have to simulate this magnetic field orientation (**Figure 5**). Field lines that are orthogonal to the IC housing only occur in special cases. These orthogonal fields can be generated with the magnetic field probes from the ***RF 1*** and ***RF 2 sets*** and the special ***BS 06BD-s*** field source from Langer EMV-Technik GmbH.

Electric fields are always emitted orthogonal to metallic surfaces. Hence, it follows that the copper layers inside a printed circuit board are responsible for this orthogonal field orientation. E-field sources have to simulate this orthogonal field orientation to the printed circuit board and test IC (**Figure 3**).
The ***RF-E 05*** E-field probe from Langer EMV-Technik GmbH can be used to generate local electric RF fields.

The ***P1401*** and ***P1501*** field sources are supplied by a power amplifier. The fields' variation over time corresponds to the current supplied by the power amplifier or to the voltage applied. The current that is fed into the ***P1401*** field sources is measured inside the field source with a shunt and provided as a signal at the measurement output. The voltage that is present in the ***P1501*** field source is also measured inside the probe. The measured signal is also provided at the field source's measurement output.
It should be noted that the power amplifier is operated under short-circuit conditions with the *P1401* field source and under open-circuit conditions with the *P1501* field source. The power amplifier used must be stable under open-circuit conditions and short-circuit-proof.

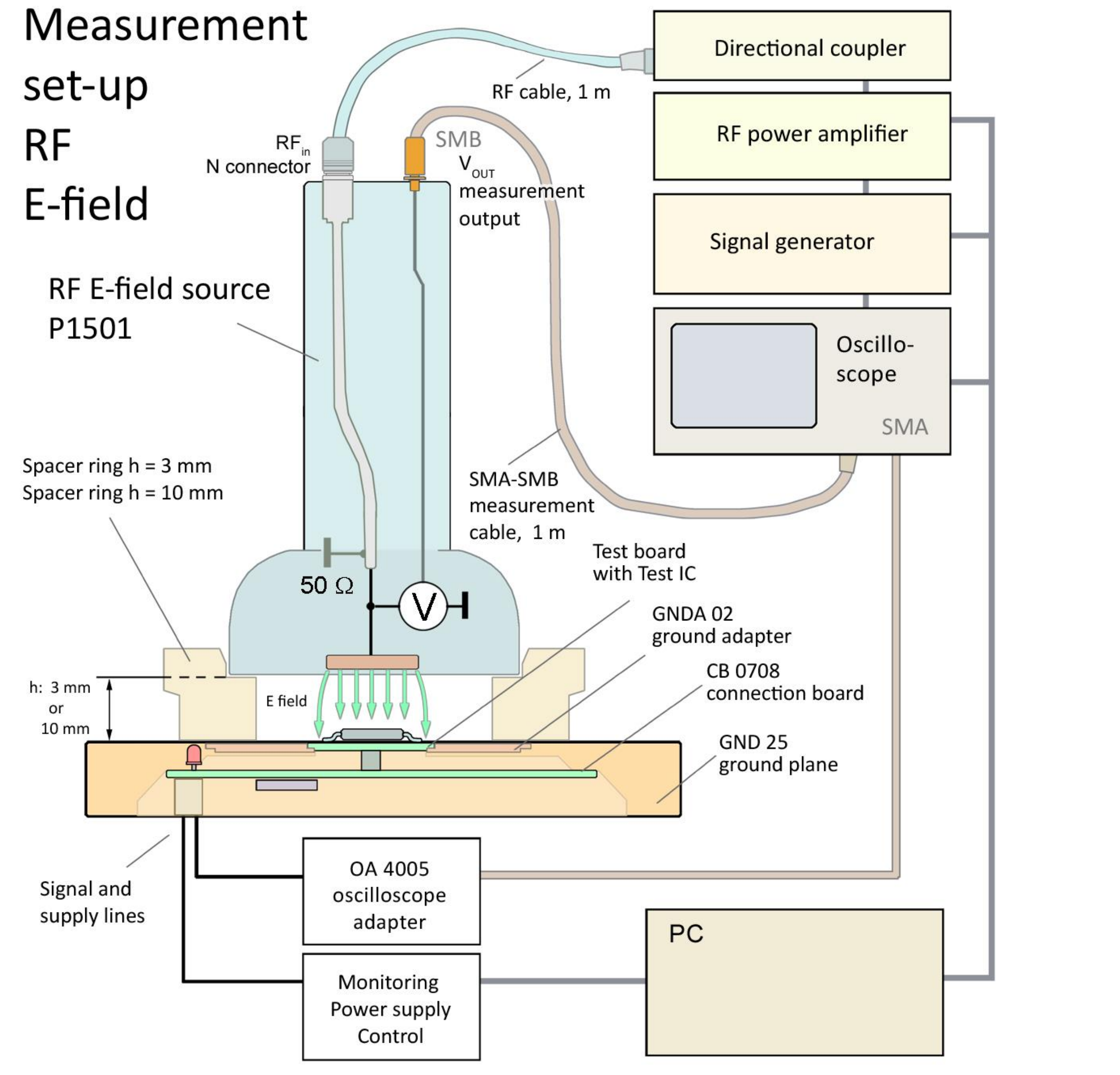


Figure 3 Test equipment: ***ICE1***[2] test environment with the ***P1501*** field source and measuring instruments

The test equipment comprises a field source from the RF field coupling probe set 1 GHz, the ***ICE1***[3] test environment and measuring instruments.

Notation:

- u, u(t), E(t): variation over time
- U, E: effective values
- U_{MAX}, $\hat{U}$: peak values
- dB/dt: $\dot{B}$

The only difference for the measurement set-ups for RF magnetic field coupling is the field source used for this purpose.

[2] ***GNDA 02*** ground adapter, ***GND 25*** ground plane and ***CB 0708*** connection board are included in the ***ICE1*** IC test environment. www.langer-emv.de The test board is described in the "***IC test instruction manual"***, mail@langer-emv.de.

[3] www.langer-emv.de

1.1 Design of the P1401 magnetic field source

Figure 4 ***P1401*** design

The field source has an RF power input (N connector) at its top to connect an RF power amplifier. The RF power input is connected to the electric conductor inside the field source (**Figure 4**). The electric conductor is at the bottom of the field source. The end of the electric conductor is connected to GND of the field source and thus causes a short circuit in the RF current path. The short-circuit current in the electric conductor generates the magnetic RF test field which emerges from the bottom of the field source. An ammeter (shunt) is located in the current path of the field source to measure the RF current (I_P) (**Figure 5**). The output voltage of the shunt is present on the field source's measurement output. The measurement output is terminated with 50 Ω in the field source.
A field chamber encloses the magnetic field which is generated by the electric conductor in the field source. The field chamber comprises the bottom of the field source, the spacer ring and the ground plane. The test IC is located inside the field chamber. It is mounted on the test board (**Figure 3**). The test board is inserted into the ***GNDA 02*** ground adapter. The ground adapter fits into the respective recess of the ***GND 25*** ground plane. [4]

[4] ***GNDA 02*** ground adapter and ***GND 25*** ground plane are included in the ***ICE1*** IC test environment. www.langer-emv.de The test board is described in the "***IC test instruction manual***".

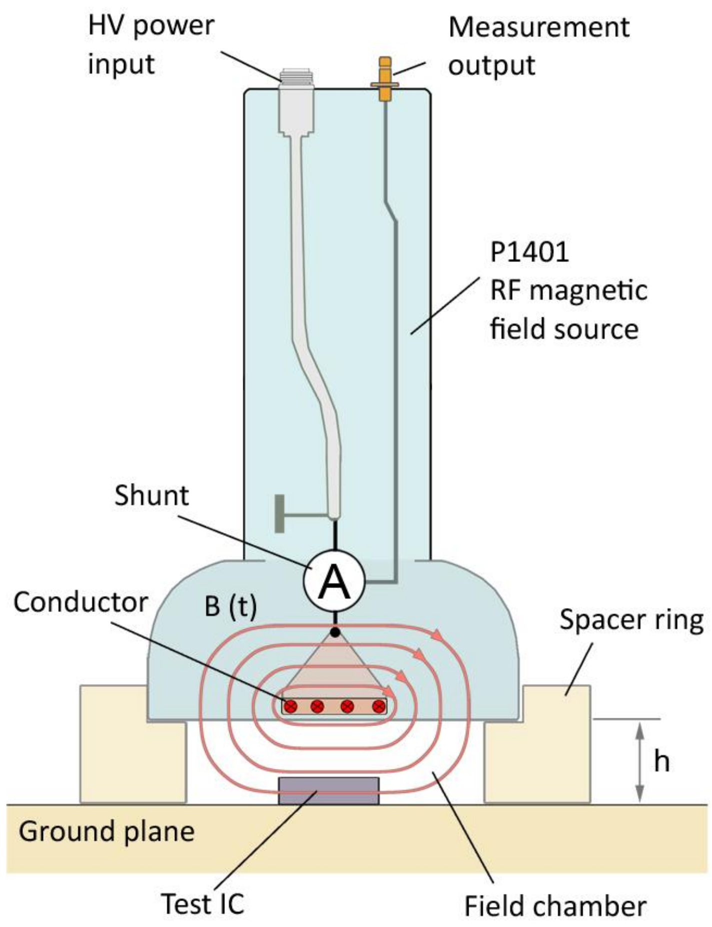


Figure 5 ***P1401*** design

1.2 Function of the *P1401* magnetic field source

The power amplifier is connected to the RF power input via a corresponding RF cable (**Figure 3**). The RF power current path runs from the power amplifier to the RF_{in} power input via the RF cable, and from there to the electric conductor and the shunt (equivalent circuit **Figure 6**). The RF current generates the magnetic field B in the environment of the electric conductor which is used to test the test IC (**Figure 5**).

The strength of the magnetic field and the voltage induced in the test IC can be determined in the following ways:

- Calculation of the magnetic flux in the area of the test IC from the measured current $i_P(t)$ and the probe constant K1 of the field source
- Calculation of the voltage $u_{IC}(t)$ induced in the test IC from the coupling inductance L_h between the electric conductor and test IC and from ω $i_P(t)$
- Calculation of the current $i_{IC}(t)$ transferred into the test IC from the probe current $i_P(t)$ of the field source and the probe constant K3 (coupling factor; see **Figure 23**)

1.2.1 Measurement of the current i_P in the electric conductor of the field source

The probe current i_P of the field source is required to calculate the magnetic field.

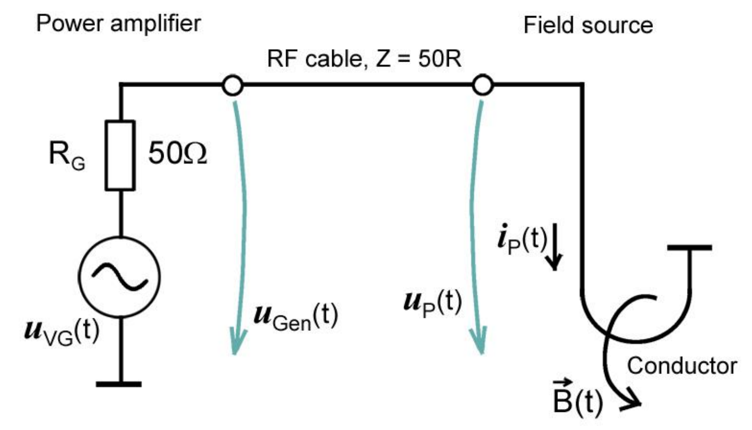


Figure 6 Equivalent circuit with the ***P1401*** field source and an RF power amplifier

The current $i_P(t)$ is measured in the field source with a shunt (0.1 Ohm). The measurement output is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The measured value u_{AV} is transmitted from the measurement output of the field source to the oscilloscope with the SMA-SMB 1m measuring cable. The attenuator has to be set to 26 dB (x20) in the vertical menu or probe head settings of the oscilloscope (**Figure 8**). The shunt's correction factor is 26 dB. The tolerance of the correction factor is smaller than 1 dB over the frequency range between 0 and 1 GHz. The correction factor (1/ K4(f)) corresponds to the inverted transfer function K4(f). The shunt's transfer function K4(f) is shown in **Figure 30**. Please refer to **Figure 30** for more precise correction values. **Eqn 1** shows the correlation between the output voltage U_{AV} of the shunt and the current I_P in the electric conductor.

$$I_P = 1/K4 * U_{AV} \qquad \text{Eqn 1}$$

Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage. An external attenuator should be used if necessary.

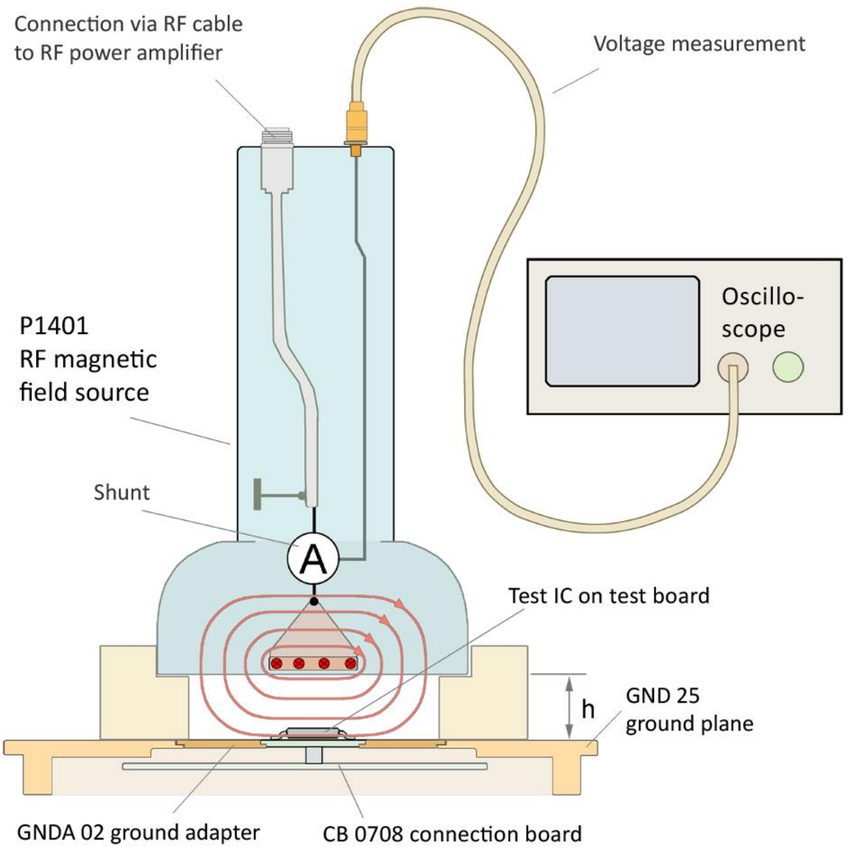


Figure 7 Current measurement at the shunt with an oscilloscope

1.2.2 Calculation of the current i_P from the forward power of the power amplifier

The forward power P_{vor} and reverse power $P_{rück}$ can be measured simultaneously with a directional coupler to determine the current $i_P(t)$. The values measured with the directional coupler, however, do not allow the representation of the variation over time to control potential harmonics.
Based on the forward power, the effective value of the (short circuit) current I_p can be calculated in a simplified way:

$$I_p = (2\ P_{vor} / R_{Gen})^{-1/2} \qquad \text{Eqn 2}$$

The current $i_P(t)$ as a function of time **Figure 8** was measured at a forward power of 5.4 W. Only the power amplifier's internal resistance R_{Gen} of 50 Ohm are on the current path. This allows the calculation of the current's effective value on the basis of **Eqn 2**:

$$I_P =(2 \cdot 5.4\ W / 50\ Ohm)^{-1/2} = 460\ mA \qquad \text{Eqn 3}$$

Figure 8 shows the measured current C1: $i_p(t)$ as a function of time. The peak value $C1_{Max}$ has been entered in the central lower box. It has to be converted into the effective value in order to allow a comparison with the value determined from the forward power:
805.9 mA / 1.414 = 569 mA.
The current I_p (460 mA) obtained by a simplified calculation from the forward power is approx. 20 % lower than the current I_p (569 mA) measured at the shunt of the field source. Due to its low precision, the current value obtained through the simplified calculation can only be used for estimates.

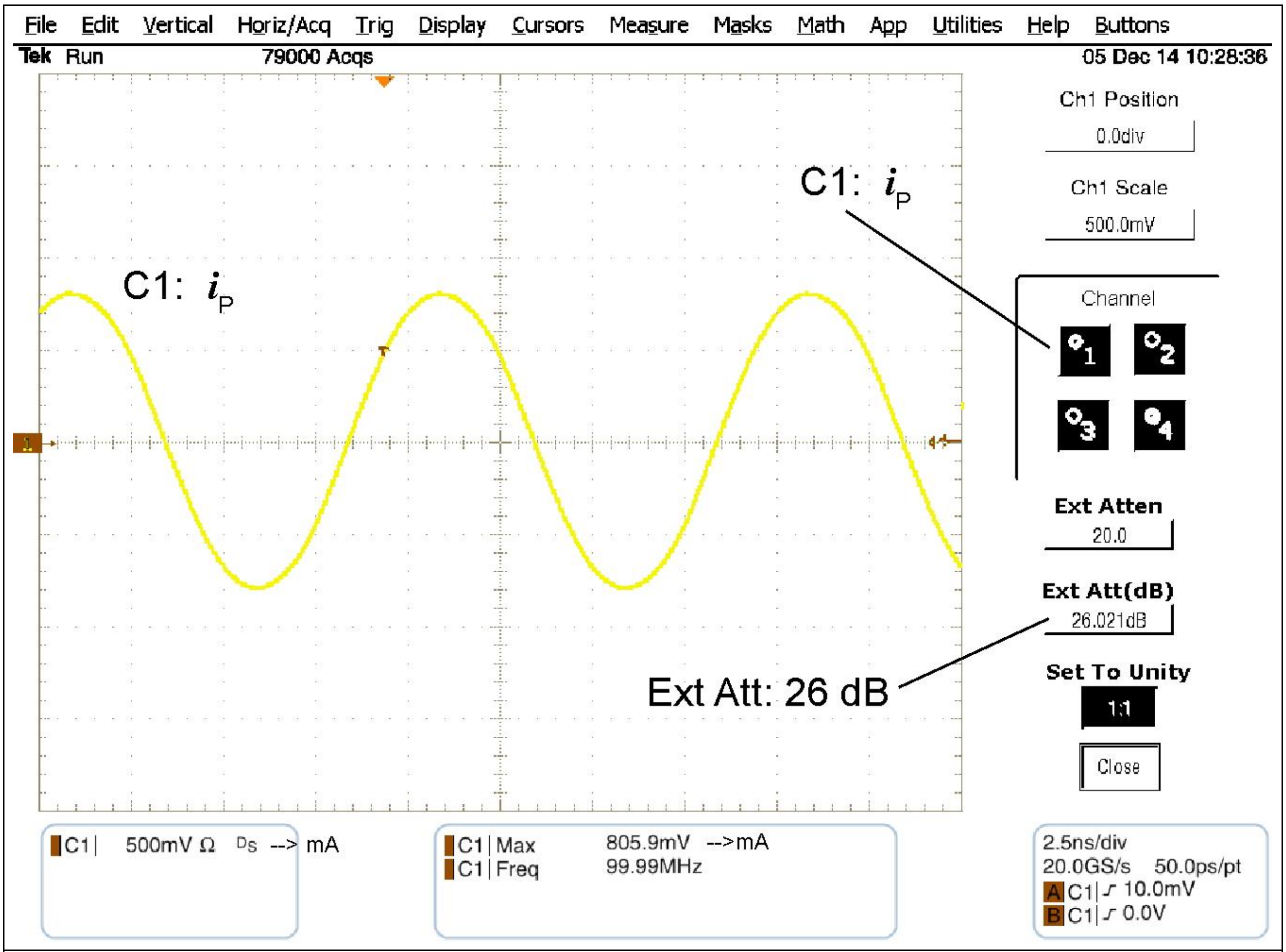


Figure 8 Curve of the current measured at the shunt (0.1 Ohm) of the ***P1401*** magnetic field source at a forward power P_{vor} of 5.4 W. Right: Shunt correction factor 26 dB set in the oscilloscope.

1.2.3 Temporal and spatial variation of the probe current i_P

The ***P1401*** field source has no terminating resistor in the RF current path and is thus not matched to the power amplifier. Due to the missing terminating resistance R_P in the ***P1401*** field source, it provides twice the current and thus twice the interference ability of a system which is terminated with 50 Ohm at the same driving generator voltage (U_{VG}).

Reflections will occur due to this missing termination and these in turn cause standing current waves in the cable leading to the power amplifier. **The power amplifier used for this purpose must be stable under open-circuit conditions and short-circuit-proof.**

Standing current waves may occur on the electric conductor of the ***P1401*** field source if the frequency is high enough. This effect is low up to a maximum field source frequency of 1 GHz. The quarter-wave length of the standing current wave is approx. 7.5 cm at 1 GHz. It is greater than the length of the electric conductor (4 cm). The current distribution over the electric conductor is thus sufficiently constant up to 1 GHz. Zero values may occur in the current wave on the electric conductor if the field source is operated above 1 GHz (**Figure 29**).

The temporal and spatial variations of the disturbance current are transferred proportionally to the magnetic field. This means that the current drops slightly between the middle and the beginning of the 4 cm long electric conductor at approx. 1 GHz.

1.2.4 Matching the field source

The ***P1401*** field source is not matched to the power amplifier. The power amplifier operates under short-circuit conditions (**this requires a short-circuit-proof power amplifier)**. Reflections will occur due to the fact that the ***P1401*** field source has no 50 Ohm termination. These reflections cause standing current and voltage waves on the field source's RF current path and on the cable leading to the power amplifier.
Due to the missing terminating resistance R_P, the ***P1401*** field source can provide twice the magnetic flux of a system which is terminated with 50 Ohm. Furthermore, no dissipating power has to be discharged in the field source.
The variation of the disturbance current over time is transferred proportionally to the magnetic field.

1.2.5 Interference mechanism of the magnetic field B

A vortex magnetic field is generated in the field chamber when an RF current flows in the electric conductor of the field source. The vortex magnetic field B penetrates the test IC (**Figure 4**).
The test IC contains current loops (**Figure 9**). The largest current loops of the test IC are formed by the pins, bond wires, lead frames, die and ground plane. A_{IC} is the cross-section of a current loop. The vortex magnetic field B penetrates the current loop and induces the disturbance voltage u_{ind} in this loop.
This induced disturbance voltage u_{ind} can have a direct effect on signals inside the test IC or drive a disturbance current through the test IC. The disturbance current can affect the Vdd/Vss supply systems and trigger faults and/or generate voltage differences between different circuit sections.

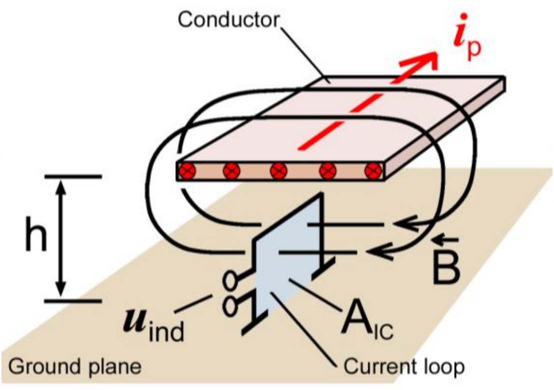


Figure 9 Operational principle behind field coupling to the test IC

The open IC loop which is shown in **Figure 9** is closed by the resistance R_{IC} (not shown in the figure). The resistance R_{IC} is formed by pull-up/pull-down resistances, driver resistances and the IC's internal resistances. The ohmic resistance of the line network establishes the resistance in supply loops (**Figure 23**).
The magnetic field's effect on the test IC loop is greatest if the magnetic field B penetrates the loop in the orthogonal direction. The loops inside the IC may have different orientations. The direction of the magnetic field has to be changed to be able to identify all critical loops. The field source can thus be rotated in the spacer ring. When rotating the field source, the direction of the magnetic field inside the field chamber is changed accordingly and all relevant loops of the test IC can be exposed to the magnetic field.
The direction of the magnetic disturbance field can be changed gradually. The different settings thus allow the application of a maximum field to the loops with different orientations inside the test IC via the pin connections or in the die. Even the orientation of critical loops in the test IC can be determined.
The level of the voltage induced and its resulting interference effect depend on parameters such as:

- value set for the forward power of the power amplifier (P_{vor}, U_{VG})
- size of the conductor loop in the test IC (A_{IC})
- distance (h) from the ground plane to the electric conductor of the field source
- angle between the electric conductor and the conductor loop

1.2.6 Calculation of the magnetic field B

The magnetic flux ϕ that is generated by the electric conductor of the field source is proportional to the probe current i_P, and the inductance L of the electric conductor is the proportionality factor.

$\Phi(t) = L \cdot i(t)$ Eqn 4

Assuming the flux density B under the electric conductor of the field source is constant and an area element A_{IC} with the associated flux Φ_{IC} is considered there (**Figure 9**), it follows that:

$B(t) = \Phi_{IC}(t) / A_{IC} = L_{IC} \cdot i_P(t) / A_{IC} = L' \cdot i(t)$ Eqn 5

where:

$L' = L_{IC} / A_{IC} = K1$ Eqn 6

is the inductance per unit length of the field chamber under the electric conductor.
This inductance per unit length is identical with the probe constant K1.

The magnetic flux in the area of the test IC can be calculated with the probe constant K1 analogous to **Eqn 5** with the following equation:

$B\,[\mu T] = K1 \cdot I_p\,[A]$ Eqn 7

where K1 depends on the metallic structure of the field chamber and electric conductor (**Figure 5**). The field chamber can be set at two different heights with the spacer rings (3 mm, 10 mm). All other dimensions of the field chamber and electric conductor are identical for all field sources. Consequently, there are two values for the probe constant K1 of the field sources at the different heights of 3 mm and 10 mm (**Table 2**). Approximate values of the magnetic flux are listed in **Table 3**.

This constant K1 is identical for all magnetic field sources (burst, ESD, RF) of the IC test system from Langer EMV-Technik GmbH.

1.2.7 Measurement of the magnetic field B

The ***BFM 02***[5] B-field meter can be used to measure the magnetic flux density B in the field chamber at the test IC location (**Figure 10**). The B-field meter is inserted into the ***GNDA 02***[6] ground adapter instead of the test board and the ground adapter has to be inserted into the ***GND 25***[7] ground plane (see user manual of the ***ICE1*** IC test environment).

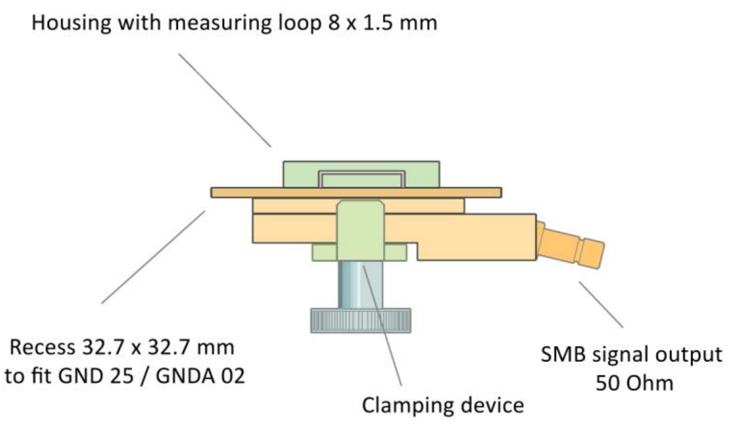


Figure 10 B-field meter to measure the magnetic flux density B

The SMB output of the B-field meter is connected to the input of the oscilloscope via the 50 Ohm SMA-SMB measuring cable (**Figure 11**). The measurement output is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The attenuator value shown on the B-field meter is entered in the vertical menu or the channel settings of the oscilloscope. The flux density is displayed on the oscilloscope in µT (or pVs/mm²) with this attenuator value.
Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage. An external attenuator should be used if necessary. A preamplifier can be used if the signal is too weak (e.g. ***PA 303***, 30 dB; www.langer-emv.de).

[5] ***BFM 02*** not included in the probe set's scope of delivery; can be ordered separately. www.langer-emv.de
[6] ***GNDA 02*** is included in the ***ICE1's*** scope of delivery. www.langer-emv.de
[7] ***GND 25*** is included in the ***ICE1's*** scope of delivery. www.langer-emv.de

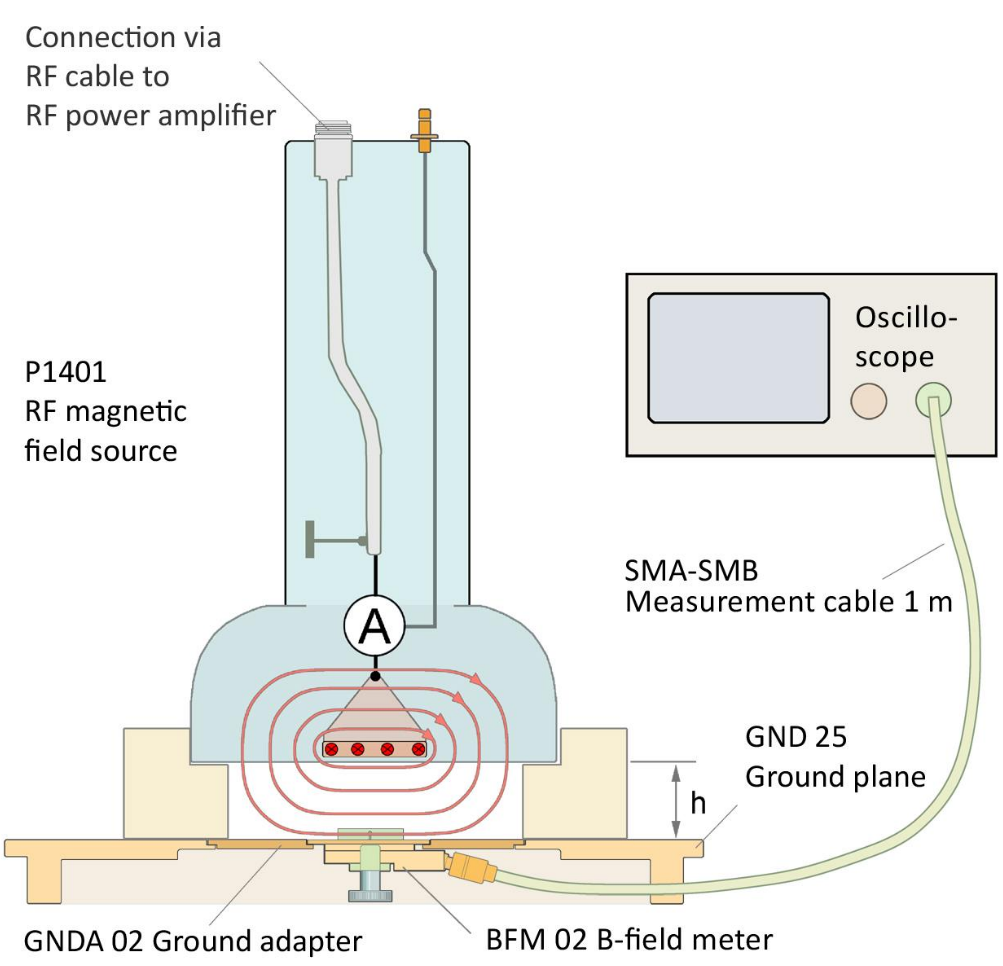


Figure 11 Measurement of the magnetic flux density of the ***P1401*** field source with the ***BFM 02*** B-field meter.

Figure 12 shows the flux density curves for a current I_{Pmax} = 805 mA (P_{vor} of 5.4 W) with a 3 mm and 10 mm spacer ring.

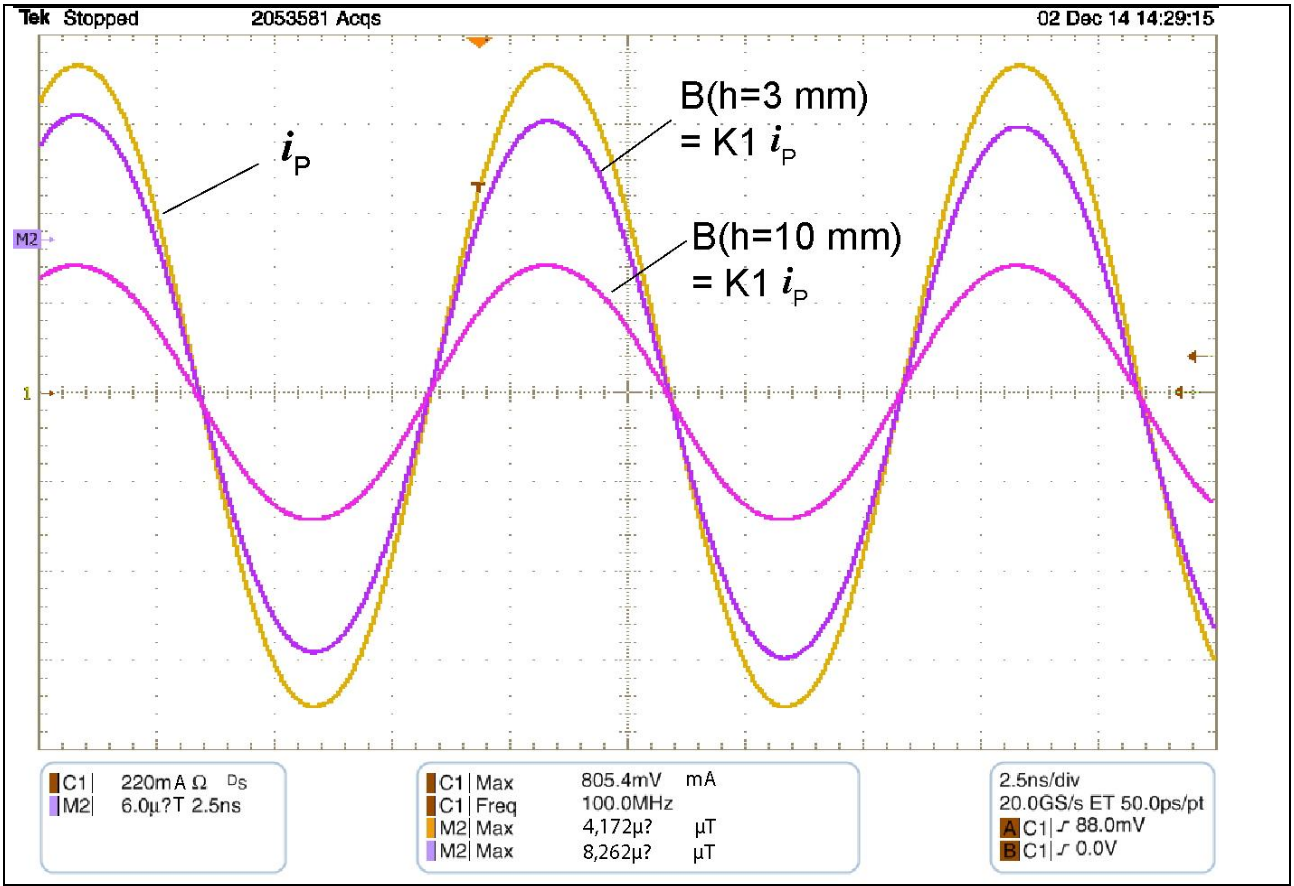


Figure 12 Flux density B variation over time in the field chamber at test IC location for the ***P1401*** field source with a spacer ring of 3 mm and 10 mm.

1.2.8 Measurement of the induction dB/dt

The ***BPM 02*** $\dot{B}$-field meter can be used to measure the dB/dt = $\dot{B}$ value in the field chamber at the test IC location (**Figure 13**) (technical data **Table 5**). The variation in flux dΦ/dt in the test IC current loop and the voltage u_{ind} induced in the test IC can be calculated on the basis of dB/dt ($\dot{B}$) and the cross-section A_{IC} of the test IC current loop:

$$A_{IC} \cdot dB/dt = d\,\Phi_{IC}/dt = -u_{ind} = -u_{IC} \qquad \text{Eqn 8}$$

The following applies in the complex case:

$$A_{IC} \cdot \omega \cdot B = \omega \cdot \Phi_{IC} = -U_{ind} = -U_{IC} \qquad \text{Eqn 9}$$

where Φ_{IC} is the magnetic flux which penetrates the IC current loop.
The ***BPM 02*** $\dot{B}$-field meter is inserted in the ***GNDA 02***[8] ground adapter instead of the test board and the ground adapter has to be inserted into the ***GND 25***[9] ground plane (see user manual of the ***ICE1*** IC test environment).

[8] ***GNDA 02*** is included in the ***ICE1's*** scope of delivery. www.langer-emv.de
[9] ***GND 25*** is included in the ***ICE1's*** scope of delivery. www.langer-emv.de

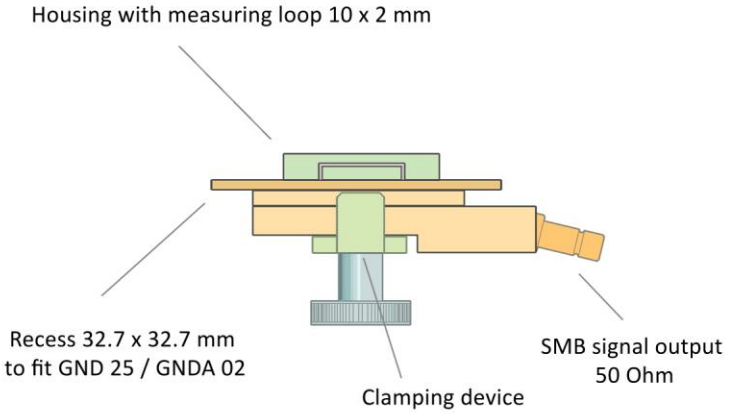


Figure 13 $\dot{B}$-field meter to measure the magnetic flux density $\dot{B}$ variation

The SMB output of the $\dot{B}$-field meter is connected to the input of the oscilloscope via the 50 Ohm SMA-SMB measuring cable (**Figure 15**). The measurement output is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The voltage U_{AV} which is present in the oscilloscope is converted to $\dot{B}$ (absolute values) for the ***BPM 02*** $\dot{B}$-field meter using the following equation:

$$\dot{B} = 1 \cdot 10^{6} \cdot U_{AV} \qquad [T/s] \qquad \text{Eqn 10}$$

The attenuator value $1 \cdot 10^{6}$ has to be entered in the channel settings or mathematical channel of the oscilloscope. When using the mathematical channel as shown in **Figure 14,** 0 dB or x1 has to be entered in the vertical menu or the channel settings of the connected channel.

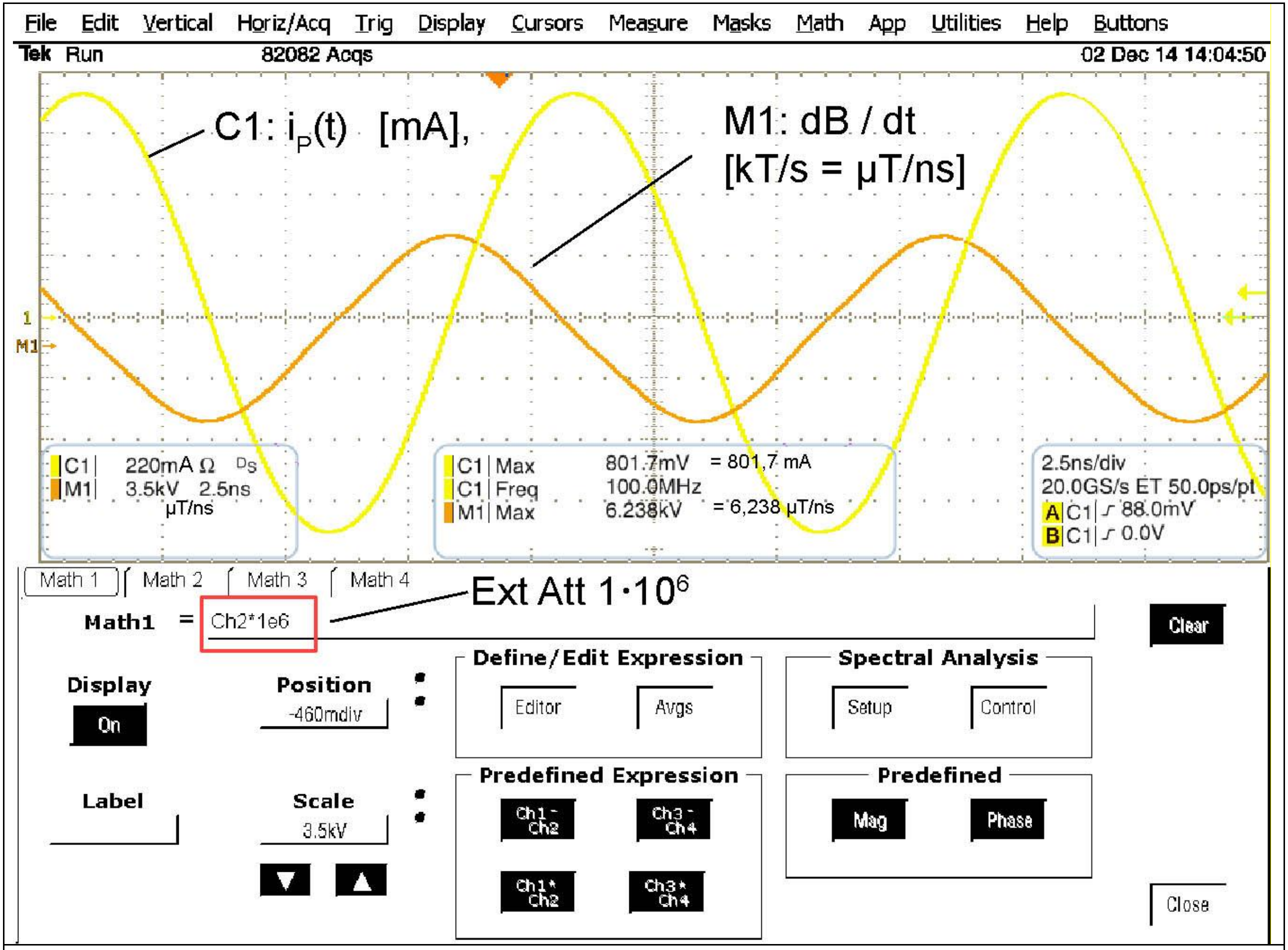


Figure 14 Setting the attenuator value for the ***BPM 02*** Ḃ-field meter in the mathematical channel of the oscilloscope, unit of measurement [T/s]

The Ḃ-field meters from Langer EMV-Technik GmbH are calibrated depending on the set-up. This is the reason why every Ḃ-field meter has its own attenuator value. This attenuator value which is shown at the Ḃ-field meter has to be used.

Ḃ is displayed on the oscilloscope in T/s with the respective attenuator value. Ḃ is displayed in V (Volt) or kV if the unit of measurement is not changed from V (Volt) to T or µT in the channel of the oscilloscope (**Figure 14**). Ḃ = 6.238 kV is displayed, for example. The value displayed in this form has to be converted using the "Meter-Kilogram-Second-Ampere system" (MKSA system) to display the value in T/s. T/s can be resolved in Vs/m² s by converting k from kV to µ/n. µVs/m² ns = µT/ns is now the channel's unit of measurement.
Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage. An external attenuator should be used if necessary. A preamplifier can be used if the signal is too weak (e.g. ***PA 303***, 30 dB, www.langer-emv.de).

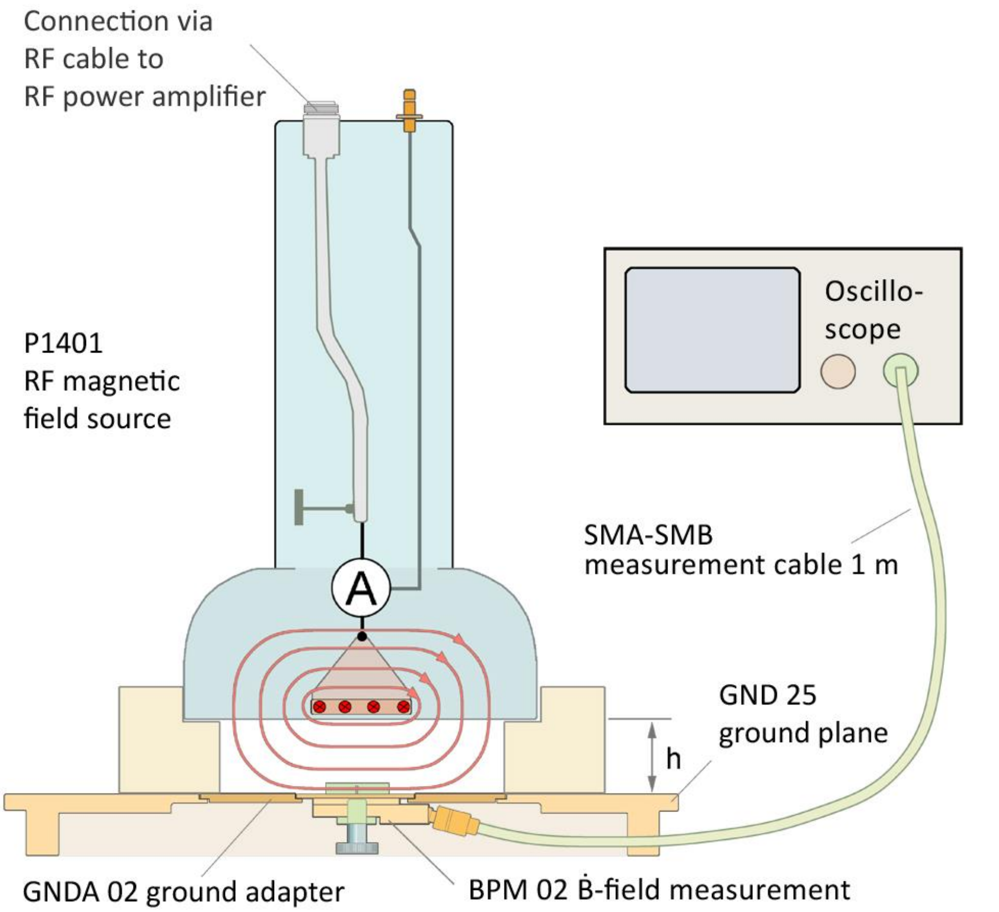


Figure 15 Ḃ measurement of the ***P1401*** field source with the ***BPM 02*** Ḃ-field meter.

If a phase relationship is to be established between the probe current $i_P(t)$ and $\dot{B}$ in the oscilloscope, the propagation delay of the field source's measuring branch and the ***BPM 02*** has to be entered in the channel settings as Deskew. **Figure 16** shows the propagation delay entered in the corresponding menu for the shunt measuring branch.

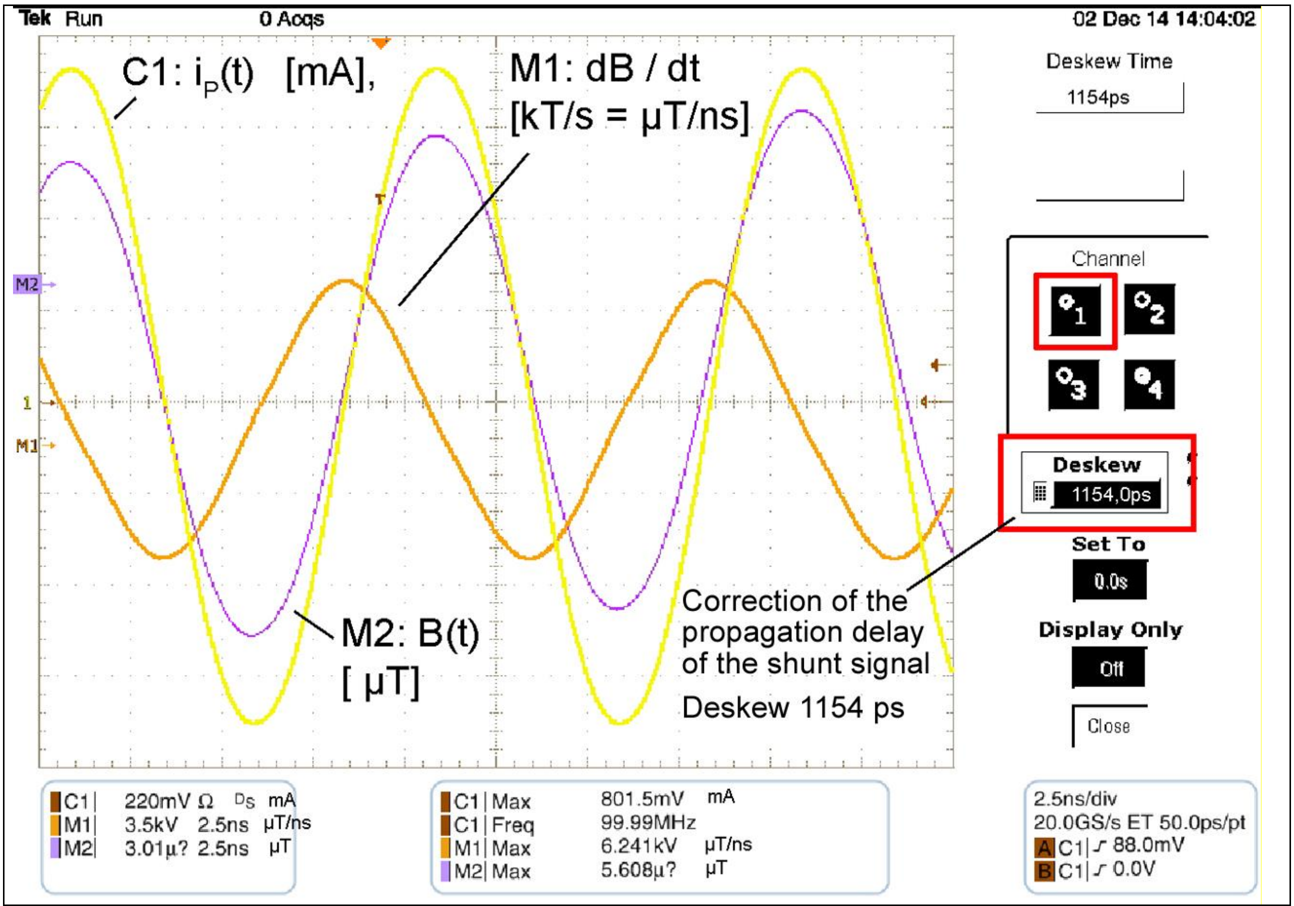


Figure 16 Propagation delays of the measuring branch from the B-field of the field source to the U_{AV} output of the shunt have to be entered in the vertical menu as Deskew.

The propagation delay of the ***BPM 02*** (**Table 5**) is entered in the corresponding measuring channel of the oscilloscope. This is channel C2 in this case. The procedure is analogous to channel C1. The propagation delay of 144 ps for **BPM 02** had already been entered in the vertical menu or the channel setting of channel C2 in **Figure 16.** The phase relations are thus shown correctly in the oscilloscope. This is clearly recognizable through the phase quadrature of dB/dt(t) relative to $i_P(t)$ and the phase coincidence between B(t) and $i_P(t)$.
An additional signal delay of 440 ps will occur if the ***PA 303***[10] preamplifier is integrated into a measuring channel. Make sure that this delay is taken into account in the oscilloscope settings to ensure in-phase measurements. It may be necessary to match every measurement set-up in correct phase relation in practice. The same types of cables have to be used for the measurements.

[10] The ***PA 303*** preamplifier is not included in the probe set. www.langer-emv.de

Figure 17 shows the $\dot{B}$ curves for a forward power P_{vor} of 5.4 W and a current I_{PMax} = 806 mA with a 3 mm and 10 mm spacer ring.

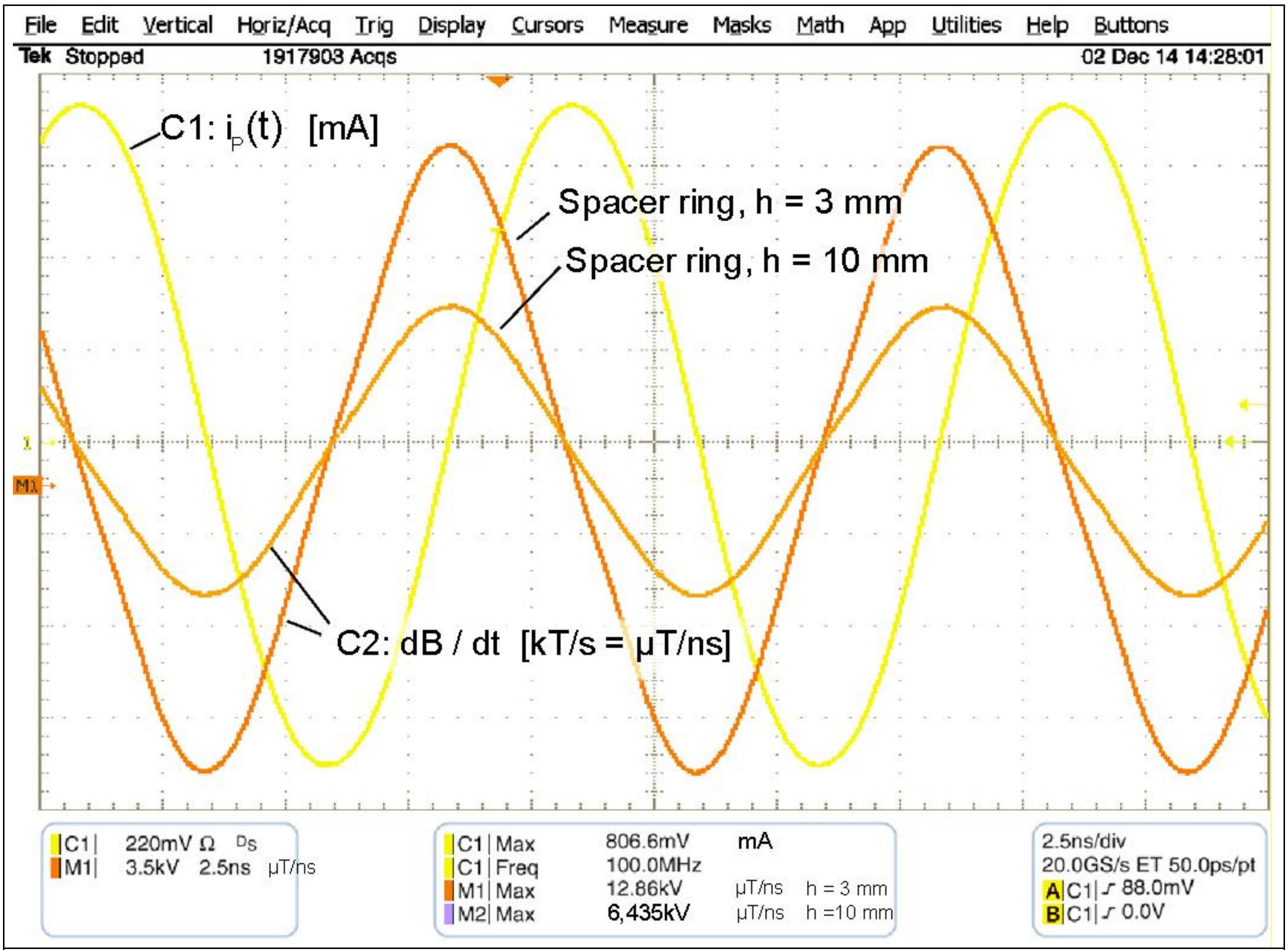


Figure 17 $\dot{B}$ field variation over time in the field chamber at test IC location for the ***P1401*** field source with a spacer ring of 3 mm and 10 mm.

The voltage that is induced in the IC can be determined if the effective cross-section A_{IC} of the IC loop is known.

$U_{ind} = A_{IC}$ [mm²] $10^{-6} \cdot \omega \cdot B$ (absolute values) Eqn 11

u_{ind} can be calculated from $\dot{B}$ with an mathematical function in the oscilloscope (**Figure 18**).

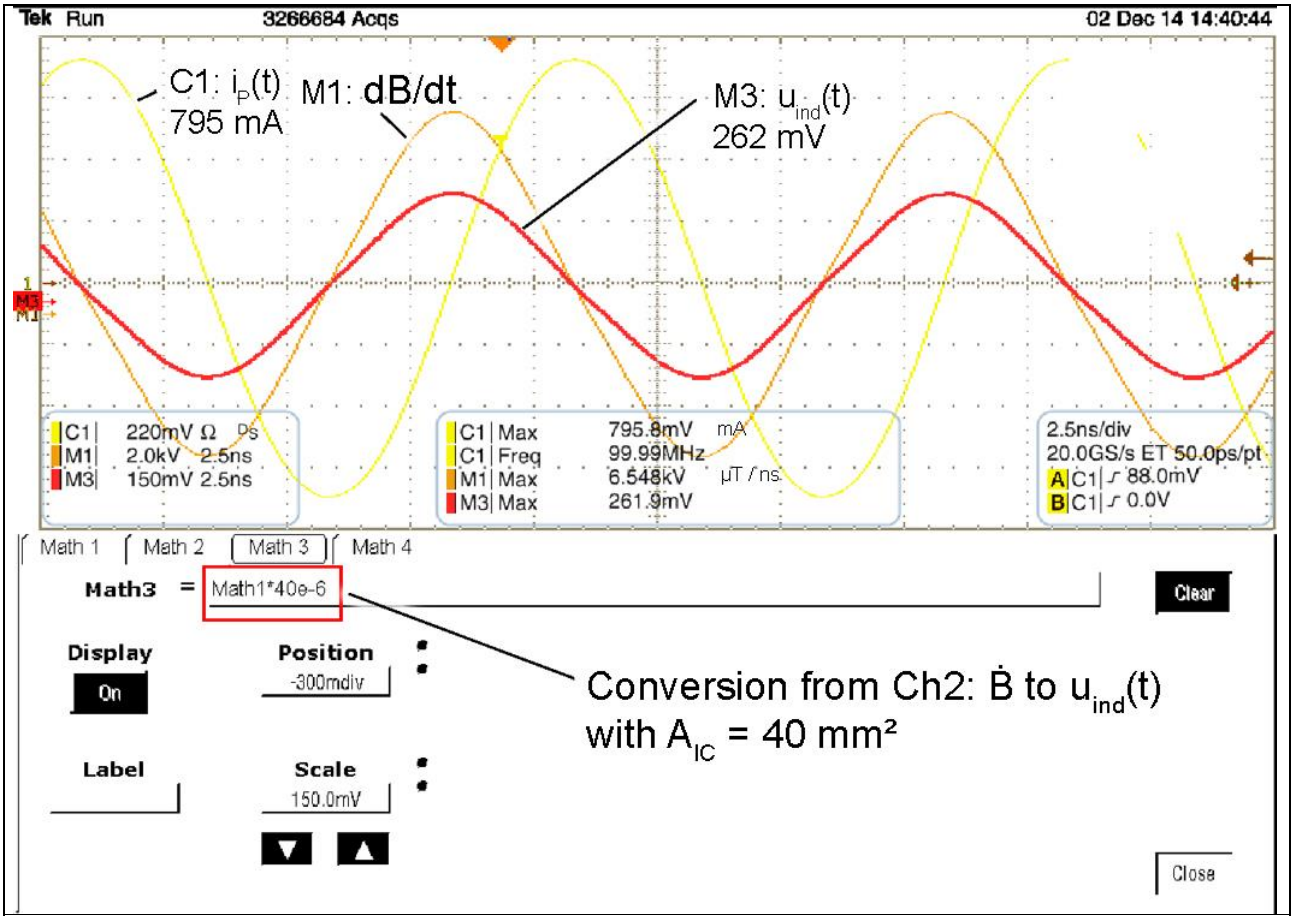


Figure 18 Induced voltage u_{ind}.calculated from $\dot{B}$ where: A_{IC} = 2 mm x 20 mm = 40 mm² is the cross-section of the IC loop, $\dot{B}$ is generated with the ***P1401*** field source, the spacer ring height is 10 mm, the power amplifier supplies i_P = 795 mA to the field source (P_{vor} 5.16 W; $P_{rück}$ 4.54 W). A voltage of 262 mV is induced in the IC loop.

The largest IC current loops are formed by the pins, bond wires, lead frames and the die. A voltage of 262 mV is induced in a loop of 2 mm by 20 mm at an RF current of 795 mA (P_{vor} 5.16 W) and a spacer ring height of h = 10 mm.

$\dot{B}$ as a function of time can be converted to the flux density B by integration.

$B(t) = \int \dot{B}(t)\,dt + C$, $B = (1/\omega)\,\dot{B} \quad (+C)$ Eqn 12

where C is the constant of integration. The integration can be performed in the oscilloscope (**Figure 19**).

The unit of measurement of the result which is calculated in the oscilloscope is T.

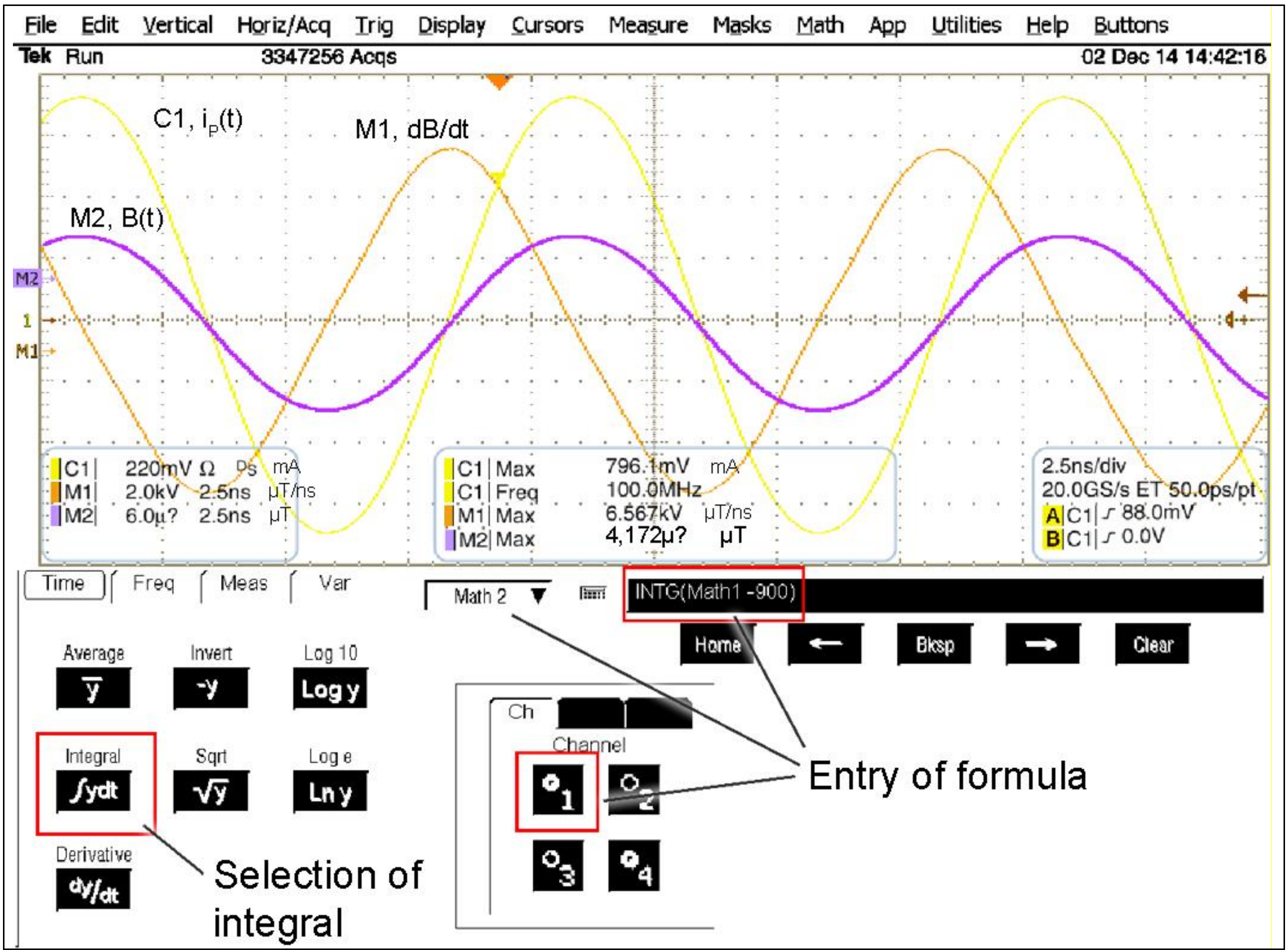


Figure 19 Entry of the integration formula in the mathematical menu of the oscilloscope, C1: $i_p(t)$, M1: $\dot{B}(t)$, M2: B(t)

The value of the constant of integration C has to be entered in the equation of the oscilloscope by hand. The final value of the constant of integration is determined by iteration. 0, for example, can be used as the initial value. If the value of the constant of integration C is too low, the measured curve will drop relative to the expected variation (**Figure 20**). The expected variation is proportional to the variation of the current $i_P(t)$ in the electric conductor **Figure 19**. The constant of integration C must be increased if the measured curve drops instead. If the measured curve rises, however, the value of the constant of integration C is too large (**Figure 20**) and then has to be reduced by hand. The value of the constant of integration has to be gradually adjusted by hand until the variation C2: B(t) as a function of time is proportional to the current C1: $i_P(t)$ (**Figure 19**). The following figures show how the correct value of the constant of integration is determined by way of example.

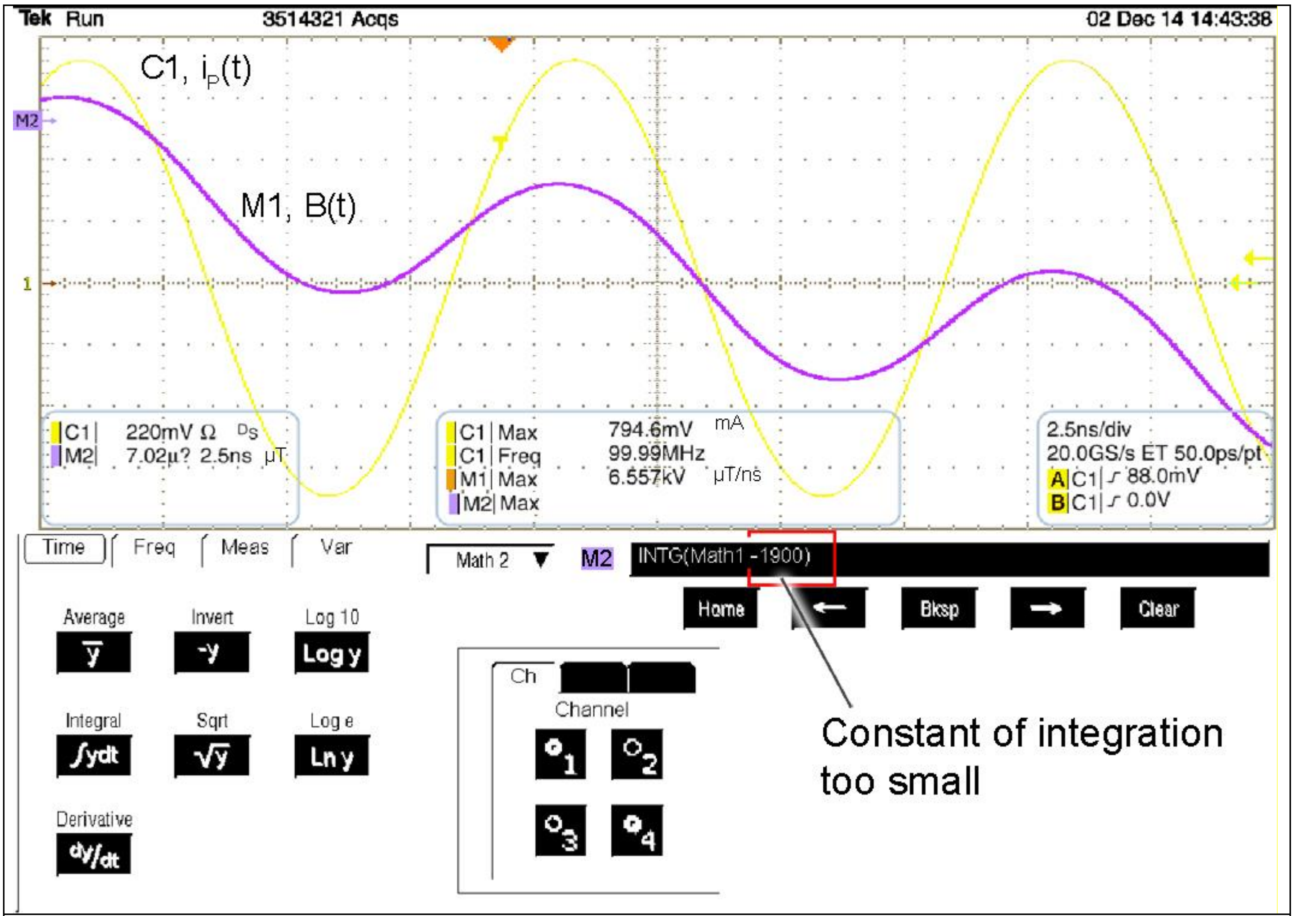


Figure 20 B-field curve M2 calculated from M1 by integration. The flux density B(t) should be proportional to the current $i_P(t)$. In contrast, B(t) (M2) drops relative to $i_P(t)$ (C1). This is due to the integration constant -1900 being too small. The constant of integration must be increased to -900, for example.

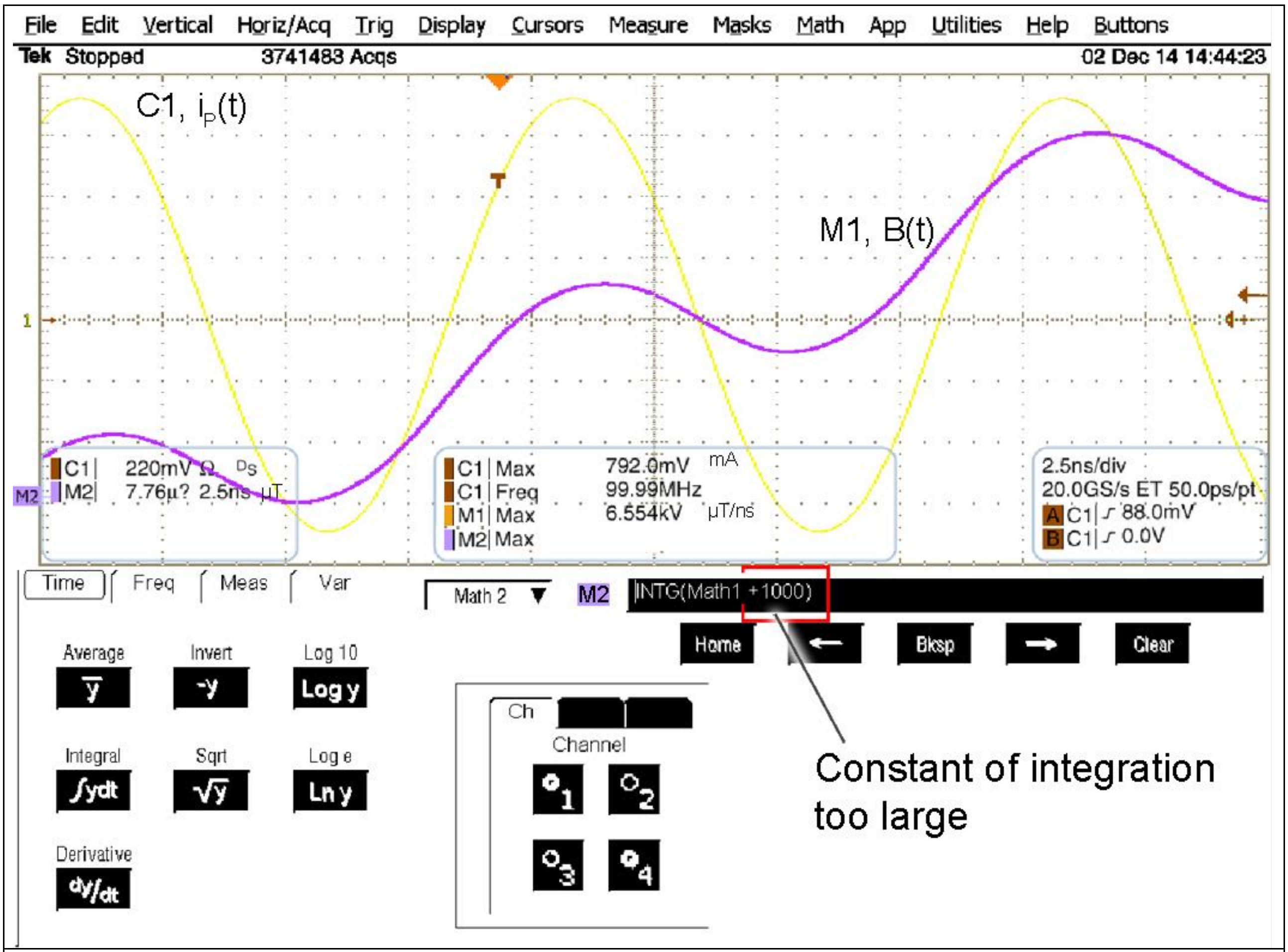


Figure 21 B-field curve M2 calculated from C2 by integration. The flux density B(t) should be proportional to the current $i_P(t)$. In contrast, B(t) (M2) rises relative to $i_P(t)$ (C1). This is due to the integration constant 1000 being too large. The constant of integration must be reduced to -900, for example.

If the attenuator value which has been entered in the oscilloscope converts the measured signal $u_{AV}(t)$ to T/ns, A_{IC} has to be entered in m² in the equation of the oscilloscope. The unit of measurement of the result displayed on the oscilloscope is then T.
If the attenuator value which has been entered in the oscilloscope converts the measured signal $u_{AV}(t)$ to mV/mm², A_{IC} has to be entered in mm² in the equation of the oscilloscope. The unit of measurement of the result displayed by the oscilloscope is then Vs/mm².

If $\dot{B}$ is measured logarithmically (in dB) with a spectrum analyser, B can be integrated in the following way:

$$B = \dot{B} - 20 \log \omega \qquad \text{Eqn 13}$$

The measurement signal can be corrected with 20 log ω by means of the ***CS-ESA***[11] software.

[11] The ***CS-ESA*** software from Langer EMV-Technik GmbH has been developed for the clear and comparable recording, documentation and analysis of a spectrum analyser's measurement curves. www.langer-emv.de.

1.2.9 Mechanism of inductive coupling from the *P1401* field source to the test IC

There are two main types of inductive coupling from the electric conductor of the field source to the loops of the test IC (**Figure 9**). The type of coupling is derived from the interaction shown in **Figure 22**.

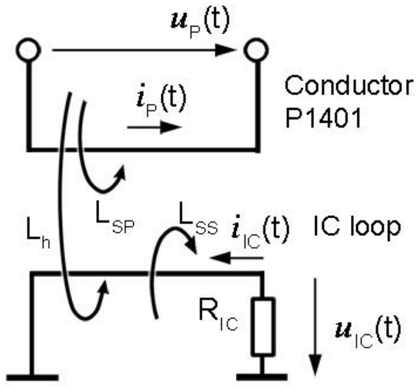


Figure 22 Interaction of the magnetic field between the electric conductor of the ***P1401*** field source and the IC loop.

The current $i_P(t)$ in the electric conductor generates a vortex magnetic field. The share of the vortex magnetic field which penetrates the IC loop is assigned to the principal inductance L_h. The principal inductance L_h mediates between the current $i_P(t)$ of the field source and the voltage $u_{ind}(t)$ which is induced in the IC loop.

$u_{ind}(t) = - L_h \cdot di_P/dt$ Eqn 14

$U_{ind}(t) = - L_h \cdot \omega \cdot I_P$ Eqn 15

The IC loop has the self-inductance L_{SS}. The interaction (**Figure 22**) can be transferred to a lumped-element transformer equivalent circuit (**Figure 23**).

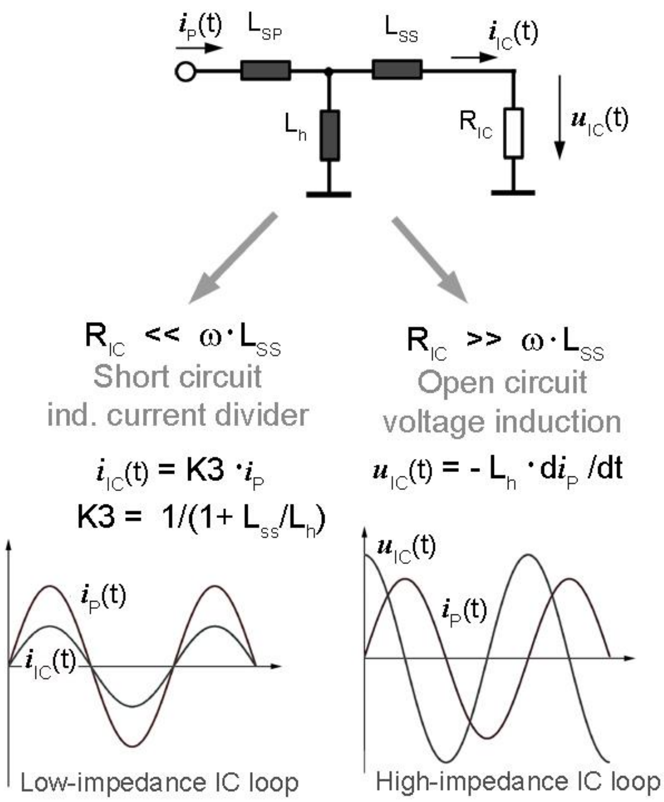


Figure 23 Transformer equivalent circuit of coupling between the electric conductor of the ***P1401*** field source and the IC loop; main types of coupling by case distinction.

1.2.10 Determining the main types of inductive coupling by case distinction:

1. Current coupling

The circuit operates under short-circuit conditions if $R_{IC} << \omega L_{SS}$. The inductances L_h and L_{SS} form a current divider. The currents are divided at the ratio L_h/L_{SS} independent of the frequency (reduced from $L_{ss} >> L_h$: $1/(1+L_{ss}/L_h) = L_h/L_s$). A proportional in-phase sine wave current $i_{IC}(t)$ flows in the test IC in the same way as in the electric conductor of the ***P1401*** field source. The peak value or effective value is attenuated by the coupling factor K3 (**Figure 23**).

Current coupling usually becomes effective ($R_{IC} << \omega L_{SS}$) if R_{IC} is in the range of 0.1 Ohm. This occurs in Vdd/Vss loops in practice.

2. Voltage coupling

The circuit operates like a voltage transformer under open-circuit conditions if $R_{IC} >> \omega L_{SS}$. The voltage induced on the inductance L_h is present in the IC (open-circuit voltage). It changes depending on the frequency according to the law of induction.

$u_{ind}(t) = - \omega \cdot L_h \cdot i_P(t)$ Eqn 16

Current components with a higher frequency generate a higher voltage. The current $i_P(t)$ is differentiated. This results in a phase quadrature (**Figure 18)**, (**Figure 23**). Voltage coupling usually becomes effective ($R_{IC} >> \omega L_{SS}$) if R_{IC} is in the range > 5 Ohm.

1.2.11 Current coupling to the IC

The L_h/L_s ratio (reduced from $L_{ss} >> L_h$: $1/(1+L_{ss}/L_h) = L_h/L_s$) determines the coupling of current to an IC loop (**Figure 23**). The ratio remains practically unchanged if the length of a current loop is changed. Changing the loop's height and line diameter would result in a change of L_{ss}. As a result, L_{ss} does not clearly depend on the loop area A_{IC}. A normalisation could only be performed under the aforementioned conditions and has not been performed in this case
The resistance R_{IC} essentially determines the effectiveness of current coupling. Current coupling is effective for supply loops due to their low resistance.
L_h can be determined on the basis of the inductance per unit length L' and A_{IC} for calculations. L_{ss} has to be determined on the basis of the IC design.

$i_{IC} = K3 \cdot i_P$ Eqn 17

Current coupling to an IC loop was determined in a measurement in **Figure 24**. The IC loop dimensions are 2 x 20 mm (A_{IC} = 40 mm²). The electric conductor of the field source was arranged at a height of h = 10 mm above GND. A forward power of P_{vor} = 5.41 W was supplied from the power amplifier to the electric conductor. The current (primary side) of the electric conductor was I_{PMax} = 789 mA when measured with a shunt. A current of I_{ICMax} = 40 mA is coupled to the IC current loop on the secondary side. The coupling factor is calculated in the following way (**Eqn 17**):

$K3 = I_{ICMax} / I_{PMax}$ = 40 mA / 789 mA = 0.05 Eqn 18

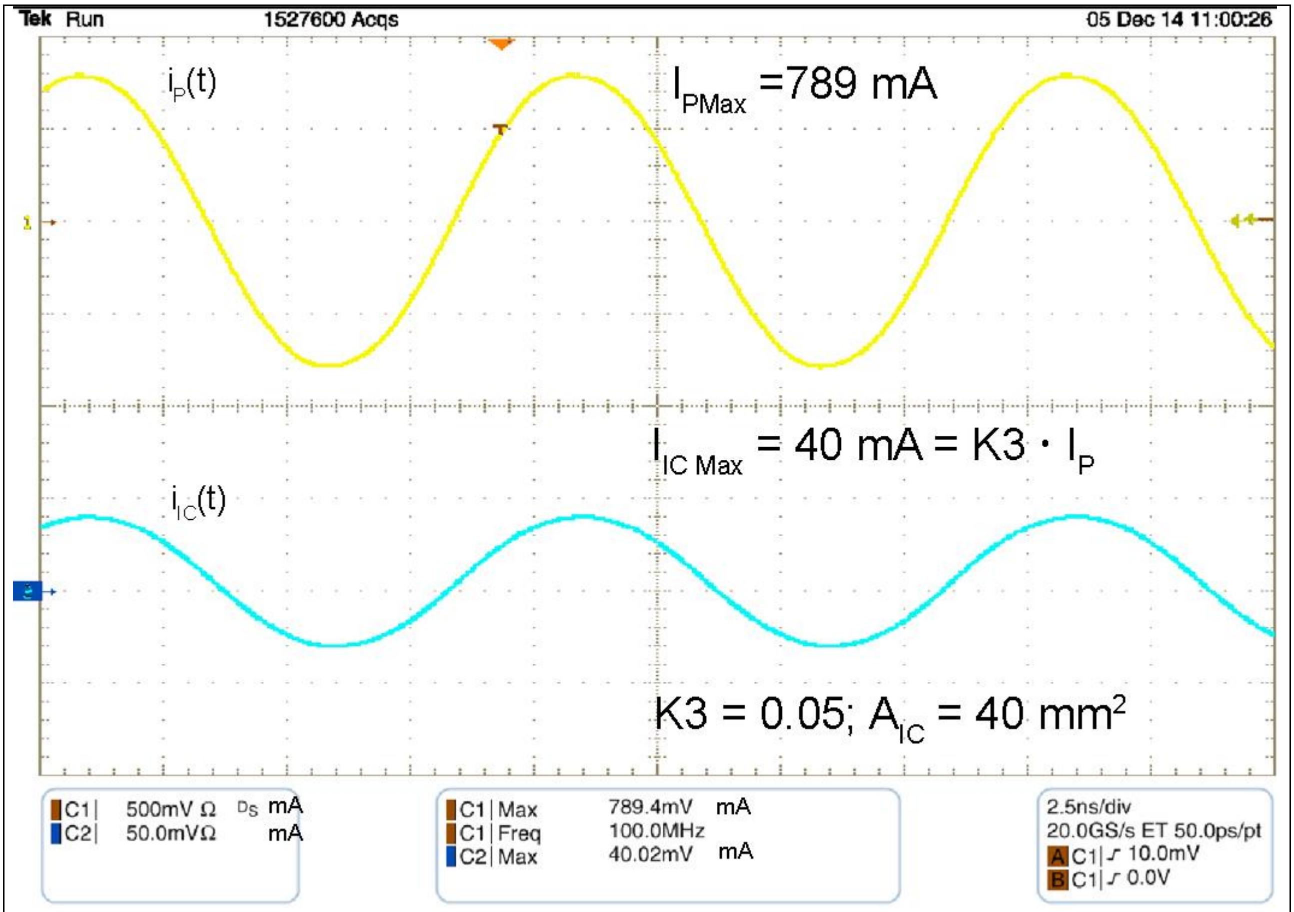


Figure 24 Current transfer to an IC loop of A_{IC} = 40 mm² and a spacer ring height of 10 mm, P_{vor} = 5.41 W. $i_P(t)$, channel C1 is the current in the electric conductor of the field source. $i_{IC}(t)$, channel C2 is the current that is transferred to the IC loop by way of a transformer.

1.2.12 Voltage coupling to the IC

The electric conductor of the field source is coupled inductively to the conductor loop in the test IC. The coupling effect is described by the law of induction.

$U_{ind} = - j\omega \cdot L_h \cdot I_P$ (in the complex case) Eqn 19

$u_{ind}(t) = - L_h{}' \cdot A_{IC} \cdot di_P/dt$ (function of time) Eqn 20

where the inductance L_h is the measure of coupling between the electric conductor and the loop of the test IC.
The specific inductance $L_h{}'$ (= K1) is the ratio between the inductance L_h and the effective surface area A_{IC} of the test-IC loop and is listed in **Table 2** for a field chamber height h of 3 mm and 10 mm. The cross-sections A_{IC} of the loops in the test IC can be determined on the basis of its design. This value, the inductance per unit length and jω I_P can be used to calculate the voltage induced in the test IC loop in the complex case, for example. These values can be used for a simulation on the IC.

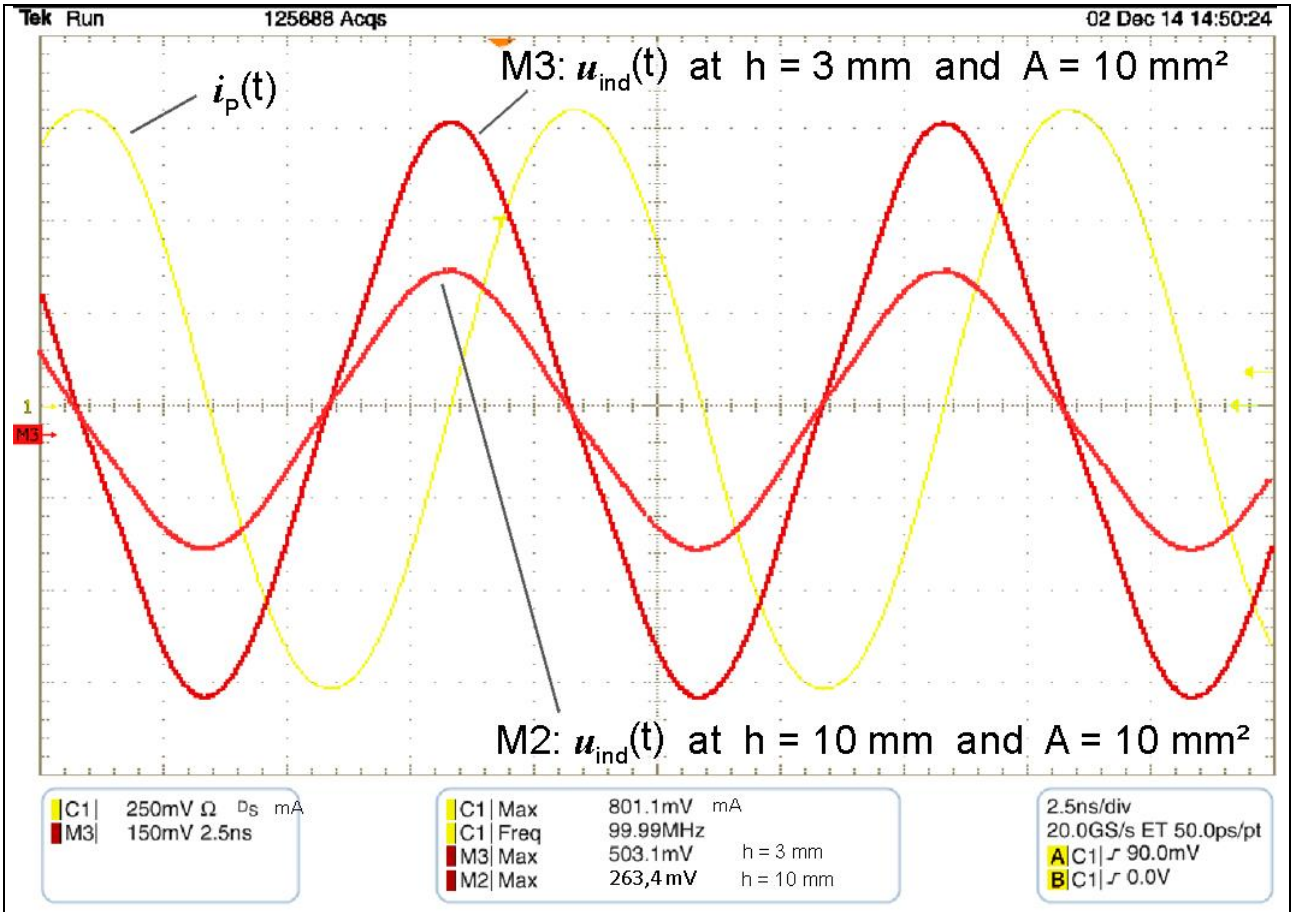


Figure 25 Voltage induced in the conductor loop of a test IC with a spacer ring of 3 mm and 10 mm and the ***P1401*** field source.

Figure 25 shows the variations of the induced voltages over time for a test conductor loop of A_{IC} = 10 mm². Twice the voltage is induced if the 3 mm spacer ring is used instead of the 10 mm spacer ring. A test IC with a 3 mm spacer ring will distort the field more than with a 10 mm spacer ring.

The induced voltage can also be calculated directly from the flux density in the area of the test IC.

$u_{ind}(t) = - A_{IC} \cdot dB(t)/dt$ Eqn 21

This equation establishes a direct relationship between the magnetic field B and the induced voltage $u_{ind}(t)$.

1.2.13 Harmonics

The power amplifier can generate harmonics depending on the frequency and modulation. **Figure 26** shows a current $i_P(t)$ as a function of time with harmonics. The current was measured with the shunt of the ***P1401*** field source. The 30 W 1 GHz power amplifier that was used in this case was operated at a frequency of 100 MHz and a forward power of 6.88 W. Varying the current $i_P(t)$ results in an overshoot of dB/dt and consequently an overshoot of $u_{ind}(t)$.

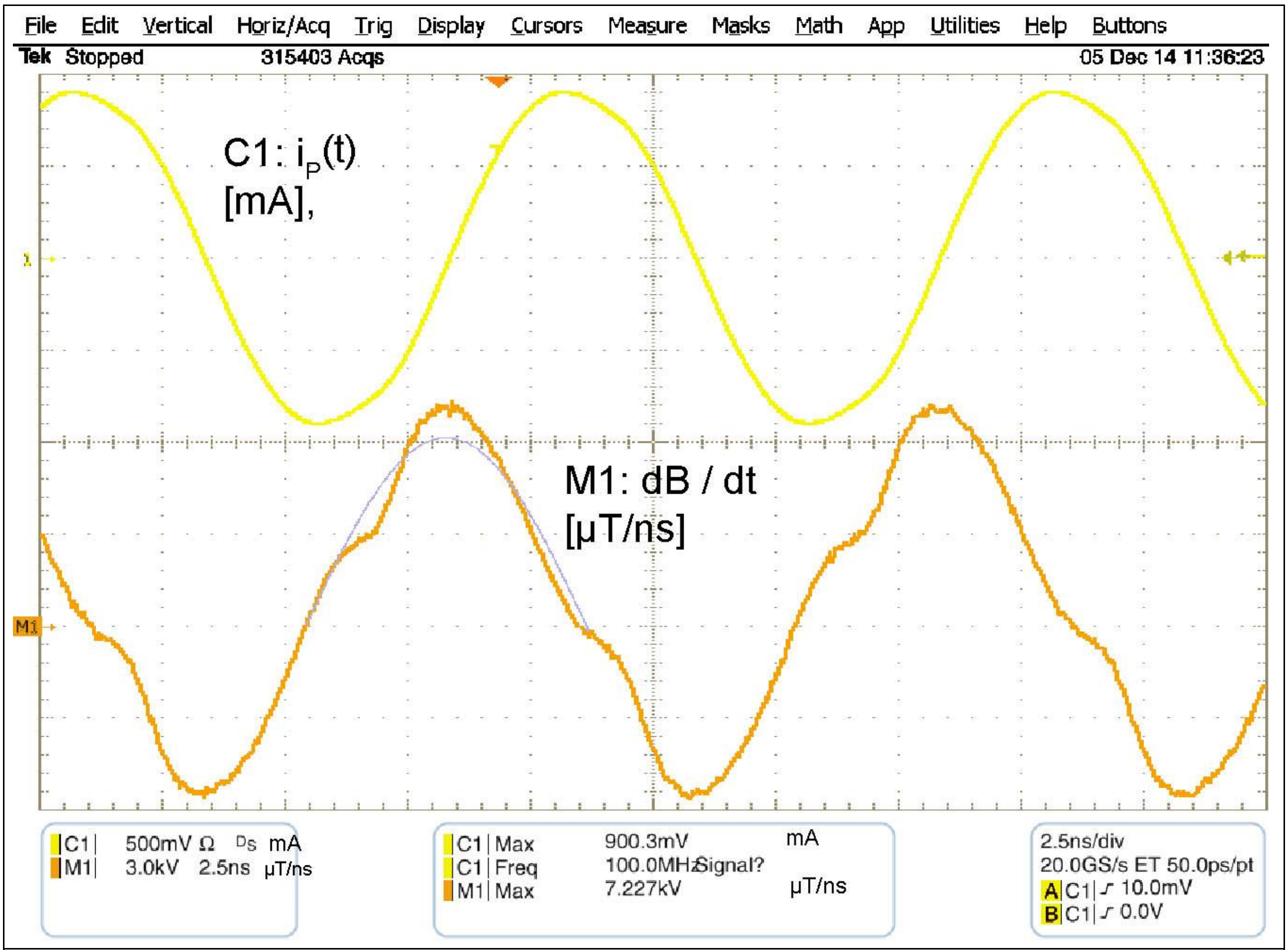


Figure 26 Current with harmonics and dB/dt curve with a 3 mm and 10 mm spacer ring and the ***P1401*** field source.

The harmonics of the current $i_P(t)$ induce a higher voltage $u_{ind}(t)$ in the IC (proportional to dB/dt). Any disturbing harmonics can be recognized at the oscilloscope if the current variation is measured with the shunt of the field source.
The measurement was repeated with the setting of 500 MHz and P_{vor} = 25 W in **Figure 27**. Fewer harmonics occur despite the higher power and higher frequency.

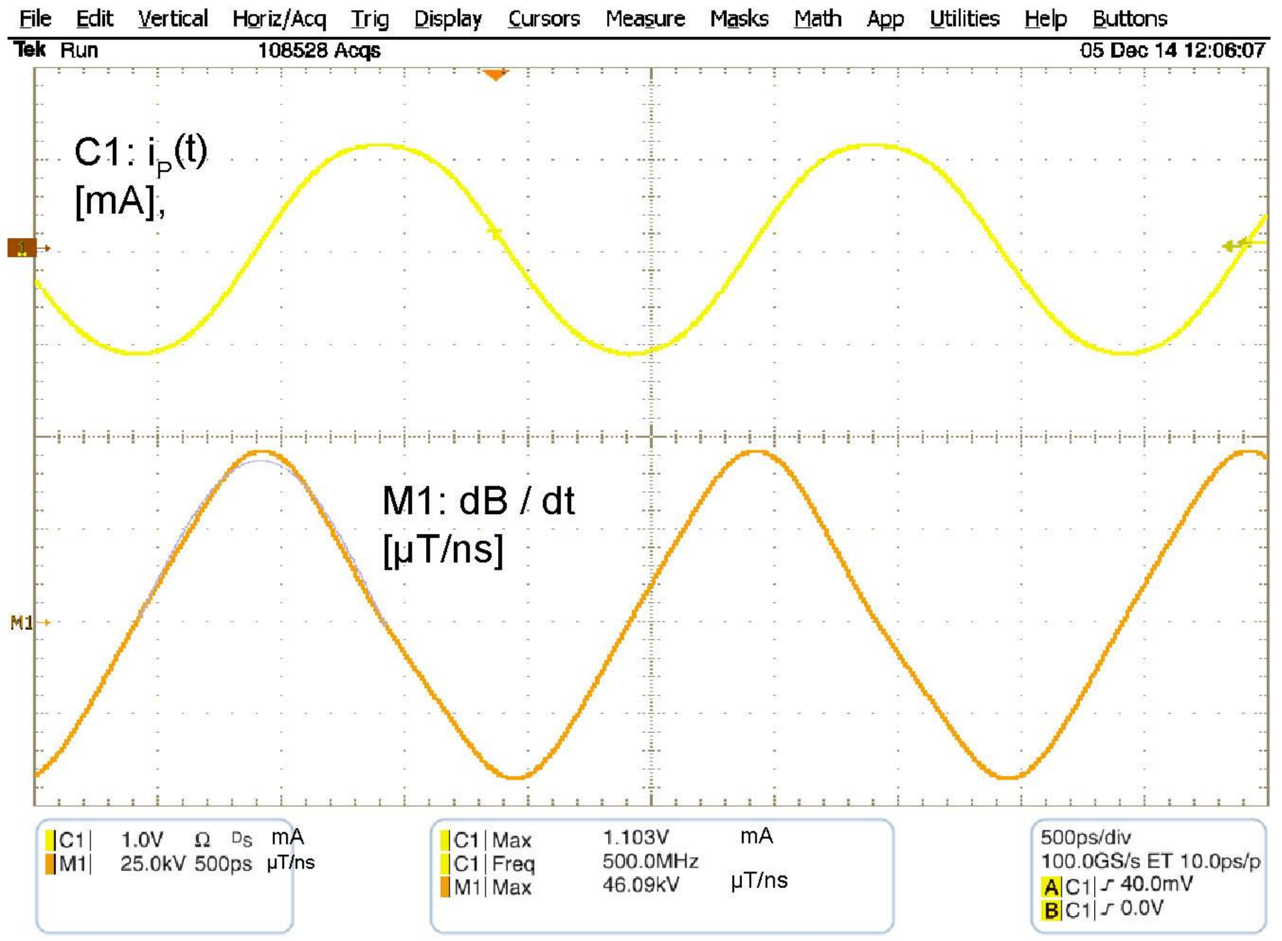


Figure 27 Depending on the setting, the power amplifier produces harmonics which are included in $i_P(t)$. They also produce harmonics in dB/dt. At P_{vor} = 25 W, f = 500 MHz and h = 10 mm.

1.2.14 Frequency response of the RF magnetic field source

Figure 29 shows the frequency response K1(f) of the current I_p in the electric conductor as a function of the flux density B. The frequency response K1(f) is almost constant at 12.4 µT/A in the operating range up to 1 GHz. The deviations are < 0.5 dB. The field source operates linearly. K1 is hardly dependent on the frequency due to the transition from electrically short to electrically long on the electric conductor of the field source.

Figure 26 and **Figure 27** allow the conclusion that current harmonics of the power amplifier may occur outside the operating range at frequencies > 1 GHz. If the frequency response K1(f) of the field source does not remain constant in this range and rises by 6 dB, for example, the peak value of the harmonics of flux density B will double. Hence, the field source's interference ability will increase. It has to be ensured that there is no substantial increase in frequency response K1(f) in the range > 1 GHz. **Figure 29** shows the frequency response up to 3 GHz (shows the third harmonics for a fundamental frequency of 1 GHz). The frequency response is shown for the beginning, middle and end of the 4 cm long electric conductor. The increase in the frequency response remains below 2 dB in all areas. A drop in the frequency response (standing wave current minima) has no negative consequences.

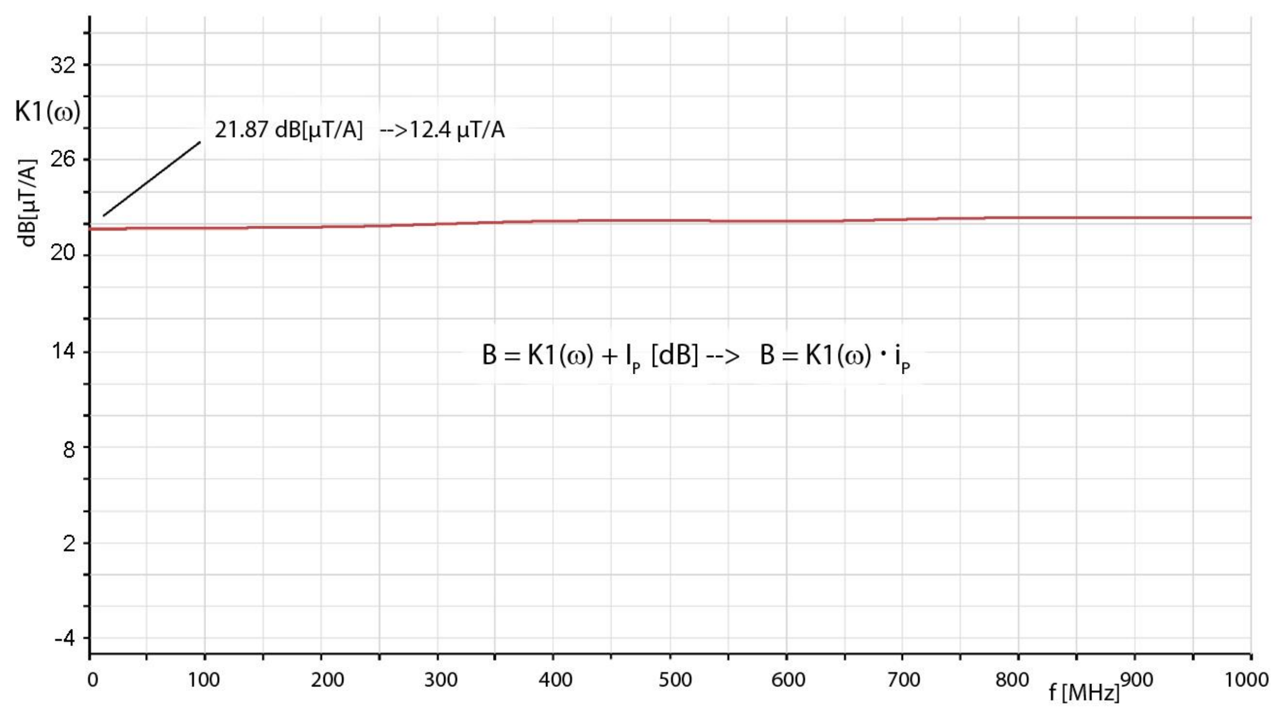


Figure 28 Frequency response of ***P1401*** K1 = B/I_P, frequency-dependent transformation of the RF current I_P to the flux density B.

Figure 30 shows the frequency response K4(f) of the 0.1 Ohm shunt up to 1 GHz. The frequency response of the shunt is similar to that of the frequency response K1(f). **Figure 31** shows that the shunt's frequency response does not rise above 3 dB up to 3 GHz.

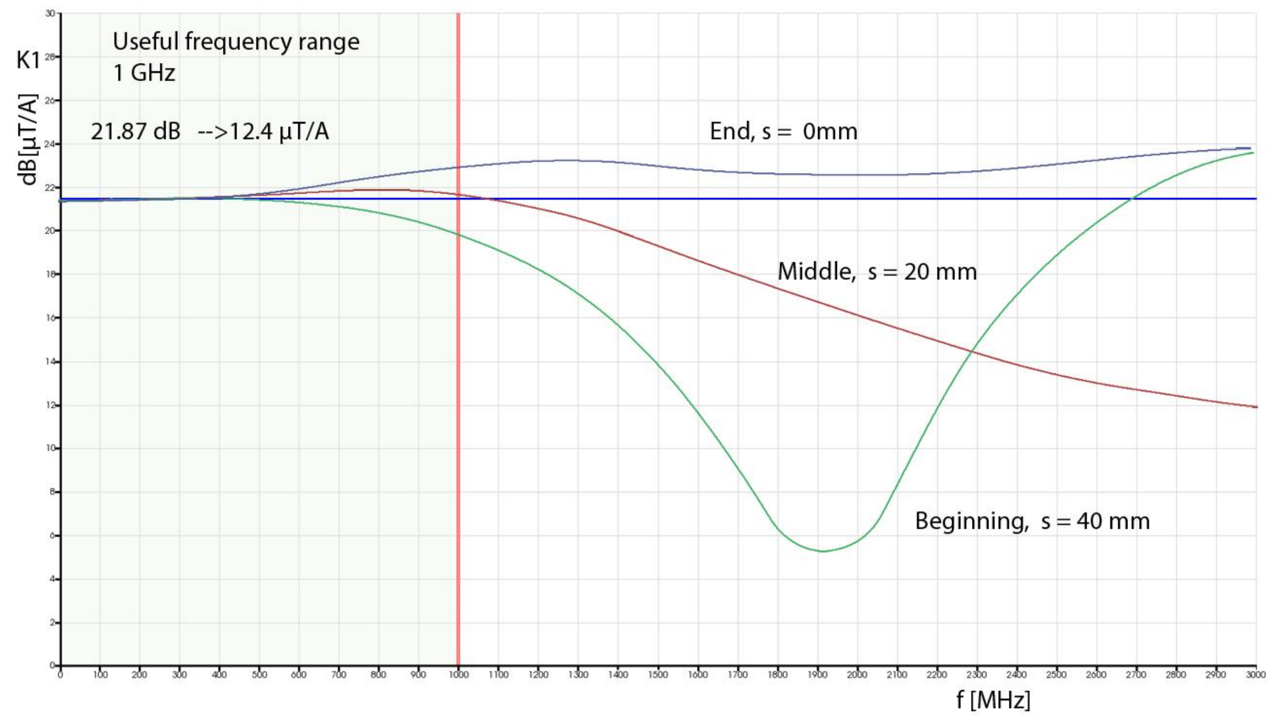


Figure 29 Frequency response K1 = B/I_P, frequency-dependent transformation of the RF current I_P to the flux density B up to 3 GHz.

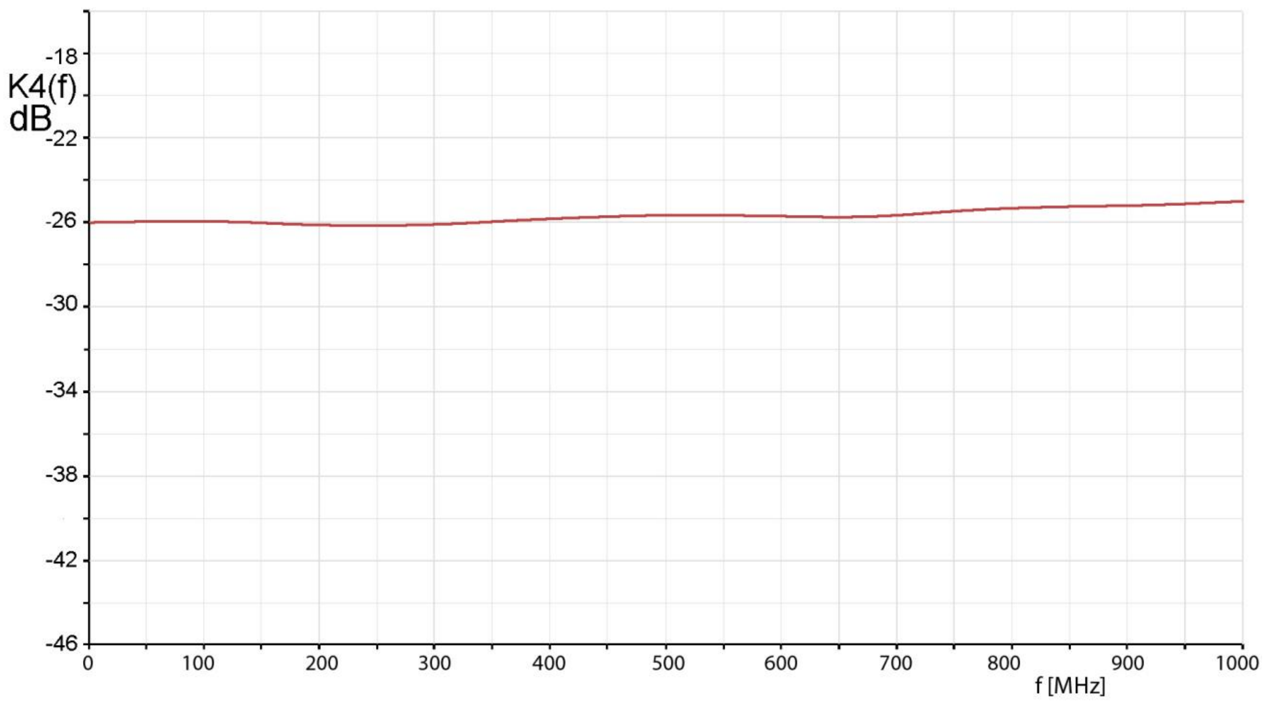


Figure 30 Frequency response of the 0.1 Ohm shunt K4(f), probe current I_p relative to the shunt's output voltage u_{AV} up to 1 GHz.

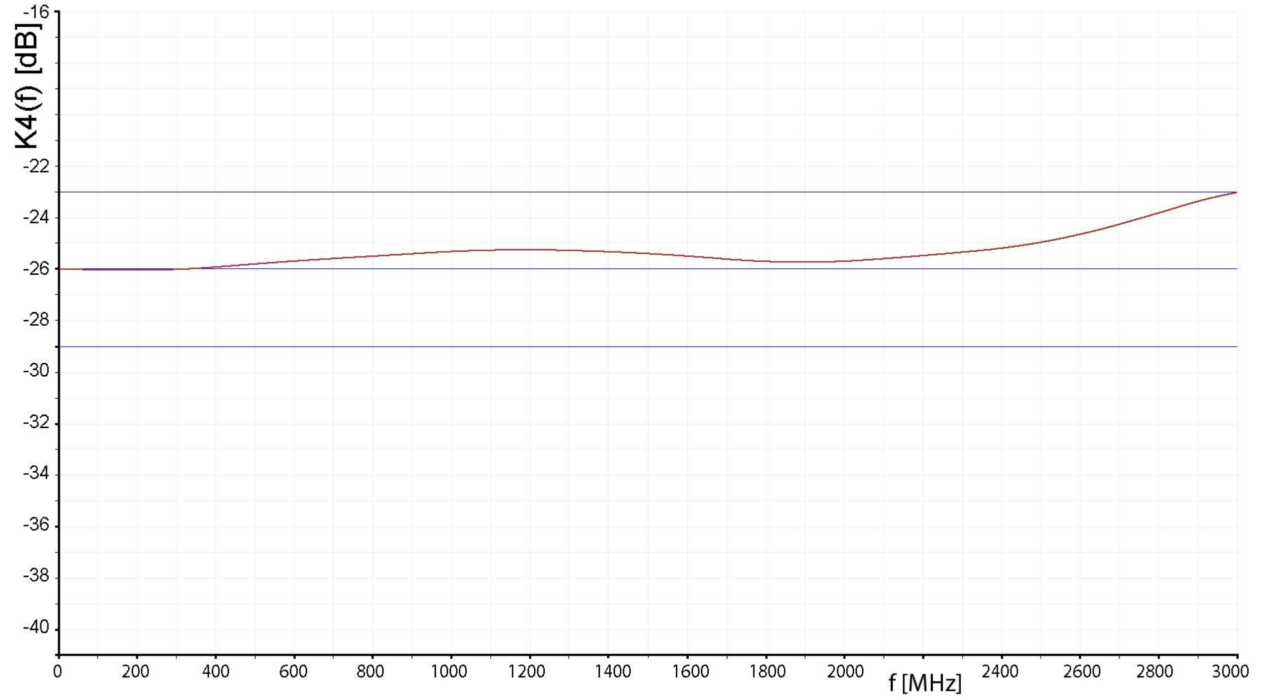


Figure 31 Frequency response of the 0.1 Ohm shunt K4(f), probe current I_p relative to the shunt's output voltage u_{AV} up to 3 GHz.

1.2.15 E-field suppression of the RF magnetic field source

A weak electric field E_P (**Figure 32**) is generated in the ***P1401*** field source as a side effect if RF is supplied to the field chamber. The electric field depends linearly on the spacer ring height and is caused either by the voltage drop on the inductance of the electric conductor ("electrically short") or standing voltage waves on the electric conductor ("electrically long"). The maximum value of the standing voltage wave can reach the generator forward voltage U_{VG}. This only occurs at points on the electric conductor which are a quarter-wave length away from the short-circuit point. This is in the supply cable outside the electric conductor for a frequency < 1 GHz, though the beginning of the voltage wave can be noticed on the electric conductor in the range of 1 GHz.
The voltage rises from the end (short-circuit point) through the middle up to the beginning of the electric conductor. **Figure 32** shows the frequency response of the field relative to the generator voltage U_{VG}. The electric field was measured at the bottom of the field chamber at a distance of h = 10 mm. The field is not zero at the end of the electric conductor at s = 0 since field lines reach the outside from the middle of the electric conductor. The electric field's unit of measurement is V/cm. The numerical value of the electric field is equal to the voltage that is present on the electric conductor at a spacer ring height of 10 mm.
20 log E/U_{VG} occurs at 1 GHz -5.5 dB or E/U_{VG} = 0.53 in the middle of the field chamber. This means that 53 % of the generator voltage U_{VG} are present against the bottom of the field chamber at 1 GHz.

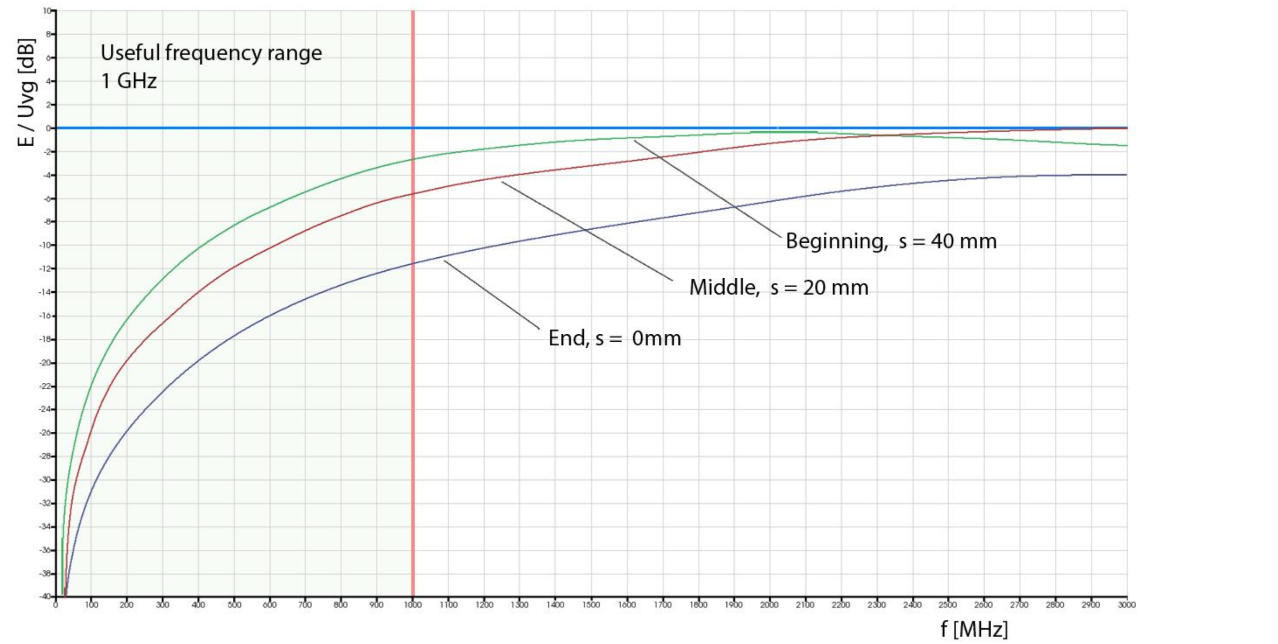


Figure 32 An electric field E_P is generated in the field chamber when the current I_P is supplied to the ***P1401*** field source. Height of spacer ring h = 10 mm.

The dependence on the current ("electrically short") results from:

$U_F = \omega \cdot L \cdot I_P$ Eqn 22

where L is approx. 4 nH for the middle of the field chamber

At 1 GHz:
$U_F = 26\ V/A \cdot I_P$ Eqn 23

(**Table 6**)

1.3 Design of the *P1501* E-field source

Figure 33 Design of the ***P1501*** E-field source

The field source has an RF power input (N connector) at its top to connect an RF power amplifier. The RF power input is connected to the electrode inside the field source (**Figure 33**). The electrode is at the bottom of the field source. It generates the electric RF field which is used to test the test IC and emerges orthogonal to the electrode from the bottom of the field source. A measurement voltage divider is located in the RF current path of the field source to measure the RF voltage ($u_P(t)$). The output voltage of the measurement voltage divider is present at the measurement output. The measurement output is terminated with 50 Ω in the field source. A field chamber encloses the electric field which is generated by the electrode of the field source. The field chamber comprises the bottom of the field source, the spacer ring and the ***GND 25*** ground plane. The test IC is located in the field chamber. It is mounted on the test board (**Figure 3**). The test board is inserted into the ground plane.[12]
The ***P1501*** field source has no terminating resistor and operates under open-circuit conditions. **Make sure that the power amplifier used is designed for operation under open-circuit conditions.**

[12] see Chapter ?

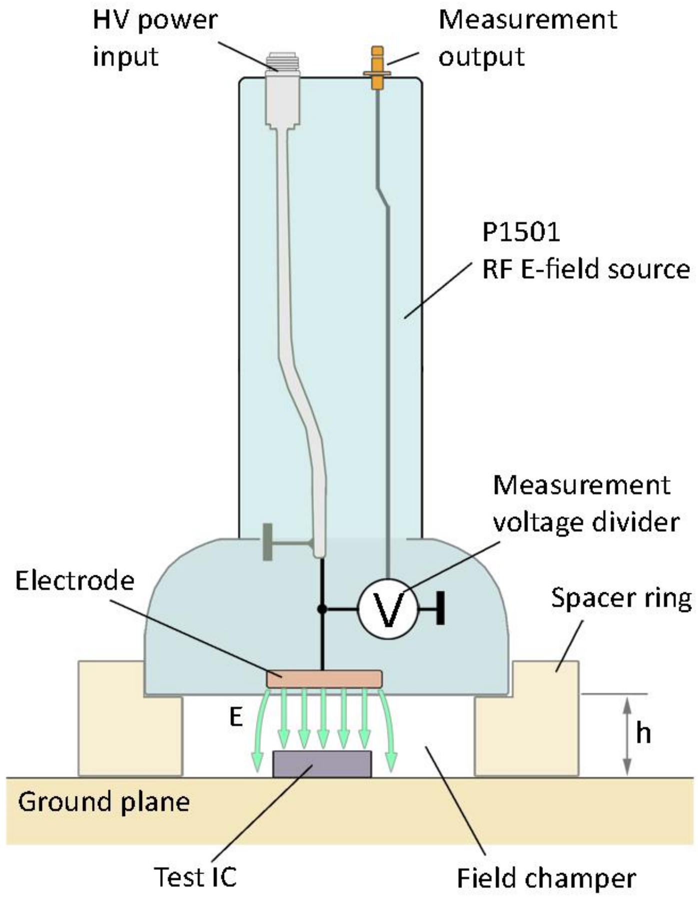


Figure 34 Design of the ***P1501*** field source without terminating resistor.

The ***P1501*** field source has two connections (**Figure 34**):

- 1 x N-connector (RF power input) to connect a power amplifier
- SMB (male), measurement output (60 dB) of the measurement voltage divider to connect an oscilloscope/spectrum analyser

1.4 Function of the *P1501* E-field source

The power amplifier is connected to the RF power input (N connector) via a directional coupler. The RF current path runs from the power amplifier to the RF power input via a corresponding RF cable, and from the RF power input to the electrode and measurement voltage divider (equivalent circuit **Figure 36**). The electrode generates the electric field E in the field chamber (**Figure 35**) which is applied to the test IC during the test (**Figure 34**).

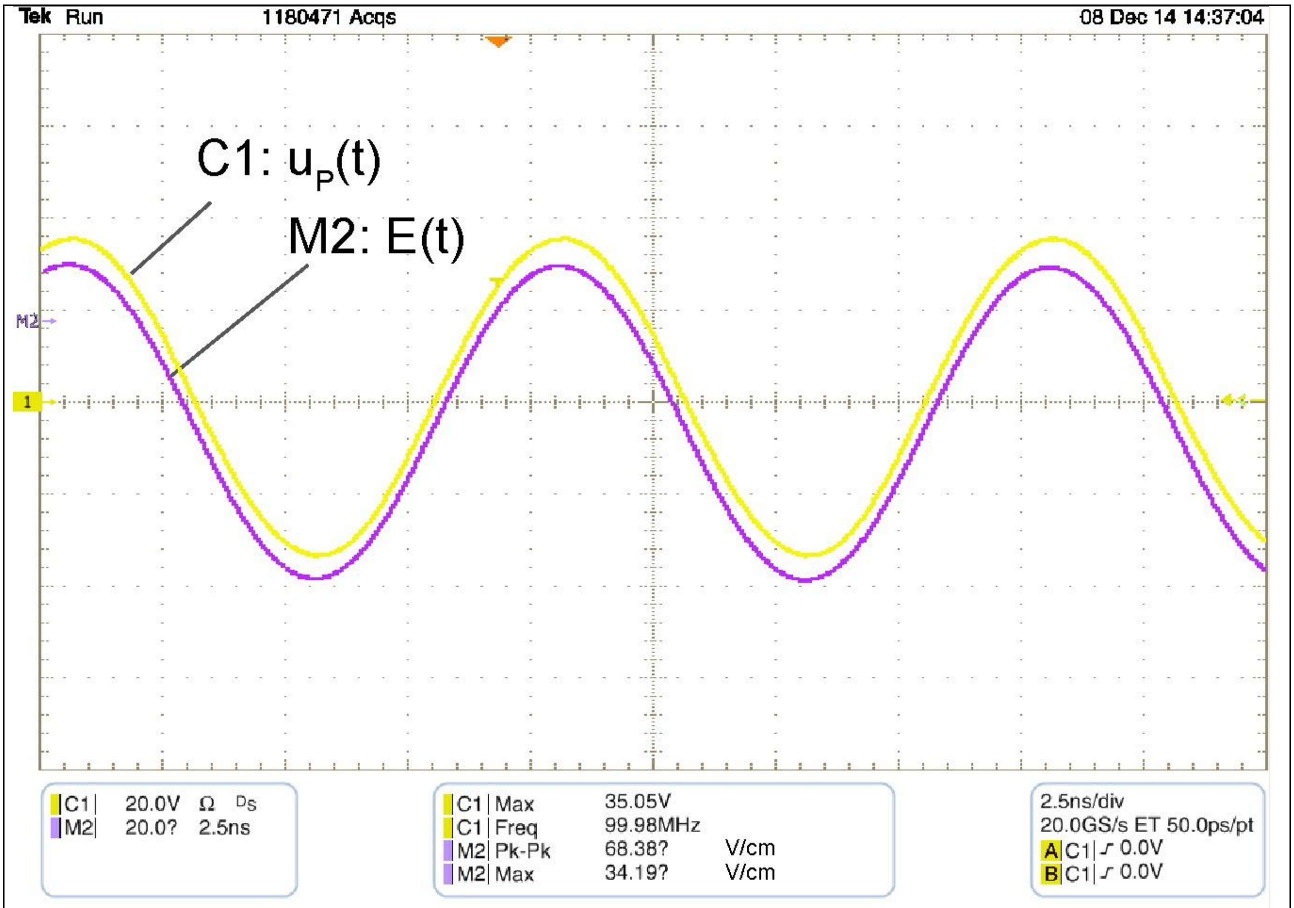


Figure 35 E(t) and $u_P(t)$ of the ***P1501*** field source at P_{Vor} 4.535 W, $P_{Rück}$ 4.07 W.

The strength of the electric field and the voltage or current which is coupled to the test IC can be determined as follows:

- **Table 8**
- Calculation of the probe voltage U_P from the forward power P_{vor} of the power amplifier in compliance with the equivalent circuit **Figure 36**
- Measurement of the voltage $u_P(t)$ on the voltage divider of the field source
- Calculation of the electric field E in the area of the test IC from the probe voltage $u_P(t)$ and the probe constant K1
- Calculation of the current $i_{IC}(t)$ coupled to the test IC from the coupling capacitance C_1 of the electrode to the pad of the test IC
- Calculation of the voltage $u_{IC}(t)$ transferred to the IC from the probe voltage $u_P(t)$ and the probe constant K3

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1.4.1 Determination of the voltage U_P on the electrode of the field source

The probe voltage $u_P(t)$ is required to calculate the electric field strength E. There are two ways to determine the probe voltage U_P.

1. **Calculation of $u_P(t)$ from the forward power of the power amplifier**

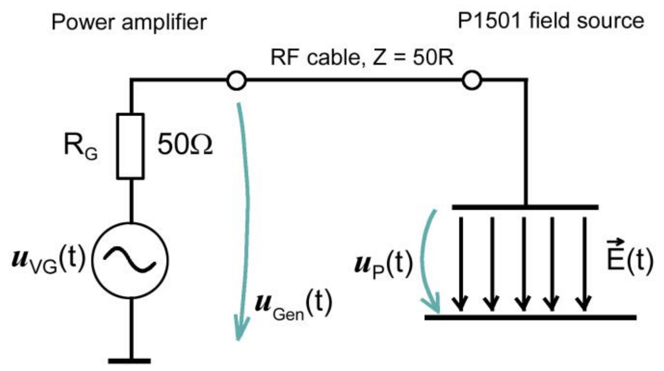

Figure 36 Equivalent circuit with a power amplifier, RF cable and ***P1501*** field source.

The ***P1501*** field source generates the voltage $u_p(t)$ on the electrode depending on the forward power P_{vor} :

$u_p = 2*(P_{vor} \cdot R_{Gen})^{-1/2}$ Eqn 24

$u_P(t)$ approximately equals $u_{VG}(t)$ for the ***P1501*** field source. (**Figure 36**).

The voltage $u_P(t)$ can be measured with the measurement voltage divider in the field source and an oscilloscope.

2. **Measurement of the voltage $u_P(t)$**

The voltage $u_P(t)$ is measured in the field source with the measurement voltage divider and divided to the voltage U_{AV} at the output. The voltage variation over time $u_P(t)$ can be shown with an oscilloscope and corresponding attenuator settings. In contrast to the directional coupler, this measuring method can be used to measure the variation over time with reference to the phase angle.
The measurement output of the field source is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The attenuator has to be set to 60 dB (x1000) in the channel settings of the oscilloscope (**Figure 38**). Provided that these values have been set, the voltage is measured by the oscilloscope in volt. **Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage.** An external attenuator should be used if necessary.
The measurement system's signal delay has to be taken into account when setting the deskew for the oscilloscope to obtain correct phase angles.

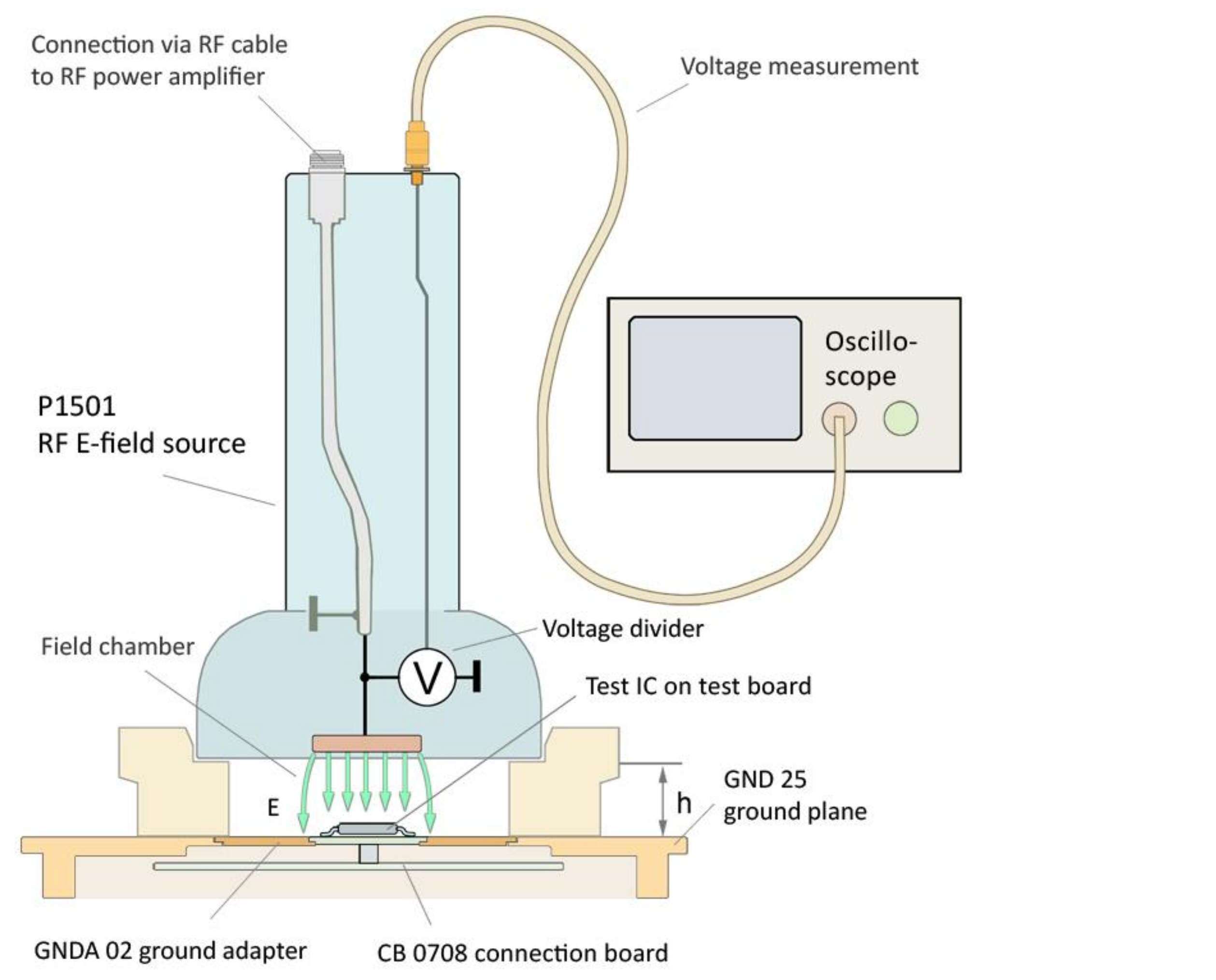

Figure 37 Voltage measurement $u_P(t)$ at the measurement voltage divider with an oscilloscope.

The voltage measurement (**Figure 37**) is much more precise than the calculation from the forward power P_{vor} of the power amplifier. **Figure 38** shows the voltage variation measured for the ***P1501*** field source over time where the forward power P_{vor} = 4.5 W. A voltage $\hat{U}_P$ of 35.15 V is present at the field source. An electric field of 35.15 V/cm or 3.5 kV/m is generated at a spacer ring height of h = 10 mm.

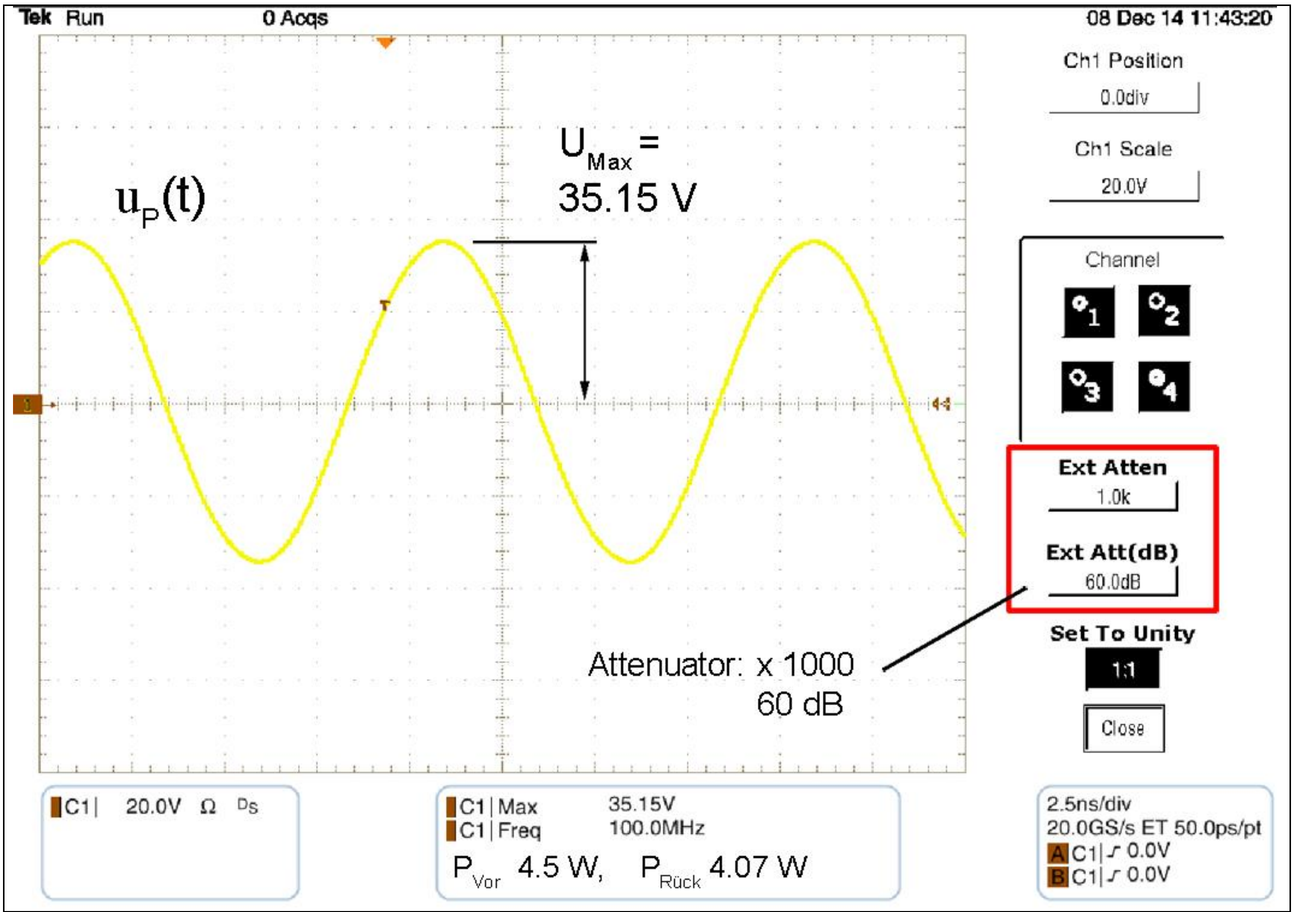

Figure 38 Voltage measurement with ***P1501***: Voltage $u_P(t)$ at a forward power of P_{vor} 4.5 W and reverse power of $P_{rück}$ 4.07 W. Attenuator set to 60 dB in the oscilloscope.

1.4.2 Matching the field source

The ***P1501*** field source is not matched to the power amplifier. The power amplifier operates under open-circuit conditions (**this requires a power amplifier that is stable under open-circuit conditions)**. Reflections will occur due to the fact that the ***P1501*** field source has **no** 50 Ohm termination. These reflections cause standing current and voltage waves on the field source's RF current path and on the cable leading to the power amplifier.

Due to the missing terminating resistor R_P, the ***P1501*** field source can provide twice the electric field strength of a system which is terminated with 50 Ohm. Furthermore, no dissipating power has to be discharged in the field source.

The variations of the disturbance voltages over time are transferred proportionally to the electric field.

1.4.3 Interference mechanism of the electric field

The voltage which is applied to the electrode of the field source generates an electric field E in the field chamber (**Figure 34**). The electric field E penetrates the test IC (**Figure 39**). Networks with metallic surfaces are located inside the test IC or at its pins. Connected metallic areas are added up to a total area. This total area is abstractly called a pad. The largest pads of the test IC are formed by the pins, bond wires and lead frames. Every pin of the test IC together with its connected lines forms a pad. The abstract pad acts as a collecting electrode for the electric field (**Figure 39**). This collecting electrode forms a plate capacitor together with the electrode of the field source.

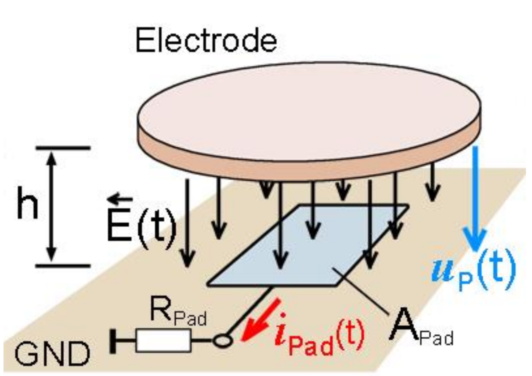

Figure 39 Operational principle behind E field coupling to the test IC.

The gap between the plates is defined as the height h. The area of a pad is defined as A_{Pad}. The electric field of the electrode contacts the pad and injects a current $i_{Pad}(t)$. The current may flow through the IC as a disturbance current or generate a disturbance voltage on R_{Pad}.
The resulting resistance of the pad to GND is called R_{Pad}. It is established by the pull-up/pull-down resistance, the driver resistance and the IC's internal resistances.
The current $i_{Pad}(t)$ generates a voltage $u_{Pad}(t)$ when it flows through the resistance R_{Pad}. The disturbance voltage $u_{Pad}(t)$ can act directly on signals and disturb signals.

The disturbance current $i_{Pad}(t)$ can flow into the IC via protective diodes. [13]
Harmful RF disturbance current demodulation can be produced, particularly through diode paths. Examples include protective diodes, reference voltage sources, inputs of bipolar OPVs, basic connections of transistors.

The level of the current coupled in the test IC and its resulting interference effect depend on the following parameters:

- value set for the forward power P_{vor}
- size of the pad in the IC (A_{Pad})
- distance (h) from the ground plane to the electrode of the field source

1.4.4 Calculation of the electric field E

The electric field in the area of the test IC can be calculated with the following equation:

$$E\,[V/cm] = U_p\,[V] / h\,[cm] = K1\,[1/cm] \cdot U_p\,[V] / [cm] \qquad \text{Eqn 25}$$

where h is the height of the electrode above the ground plane. It corresponds to the height h of the field chamber above the ground plane. The field chamber, i.e. h, can be set to two different heights with the spacer rings (3 mm, 10 mm). All other dimensions of the field chamber are identical for all field sources. K1 is the probe constant (transfer function K1(f)) of the field source ***P1501***.

The electric field is calculated in V/m with the following equation:

$$E\,[V/m] = 100 \cdot U_p\,[V] / h\,[cm] \qquad \text{Eqn 26}$$

[13] Dipl. Ing. Gunter Griessbach and Dipl. Ing. Gunter Langer, „Integrierte Schaltkreise (IC) sind heute die EMV-Schwachstellen elektronischer Geräte.“ Elektronik, 2014

1.4.5 Measurement of the electric field E

The ***EFM 04***[14] E-field meter can be used to measure the electric field E in the field chamber at the test IC location (**Figure 40**). A preamplifier can be used to carry out the measurements (***PA 303***, www.langer-emv.com). The ***EFM 04*** E-field meter fits into the ***GNDA 02*** ground adapter[15] and has to be inserted there instead of the test board[16].

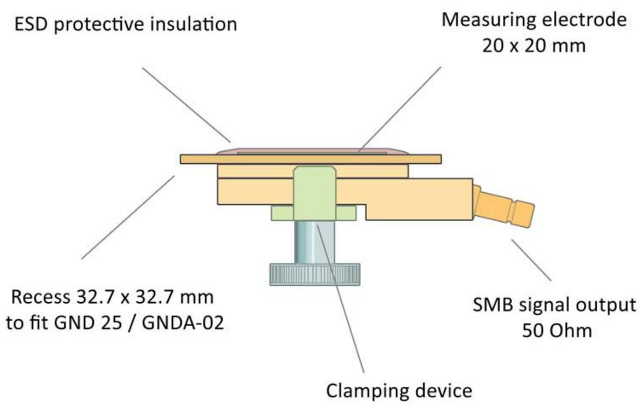

Figure 40 ***EFM 04*** E-field meter to measure the electric field.

The SMB output of the E-field meter is connected to the input of the oscilloscope via the 50 Ohm SMB-SMA measuring cable (**Figure 41**). The measurement output is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The attenuator value shown on the E-field meter is entered in the channel settings of the oscilloscope (**Figure 42**). The electric field strength is displayed on the oscilloscope in V/mm with this attenuator value.
Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage. An external attenuator should be used if necessary. A preamplifier can be used if the signal is too weak.

[14] ***EFM 04*** E-field meter is not incloded in the scope of delivery.
[15] ***GNDA 02*** ground adapter and ***GND 25*** ground plane are included in the ***ICE1*** test environment. www.langer-emv.de
[16] The test board is described in the "***IC test instructions***“, mail@langer-emv.de.

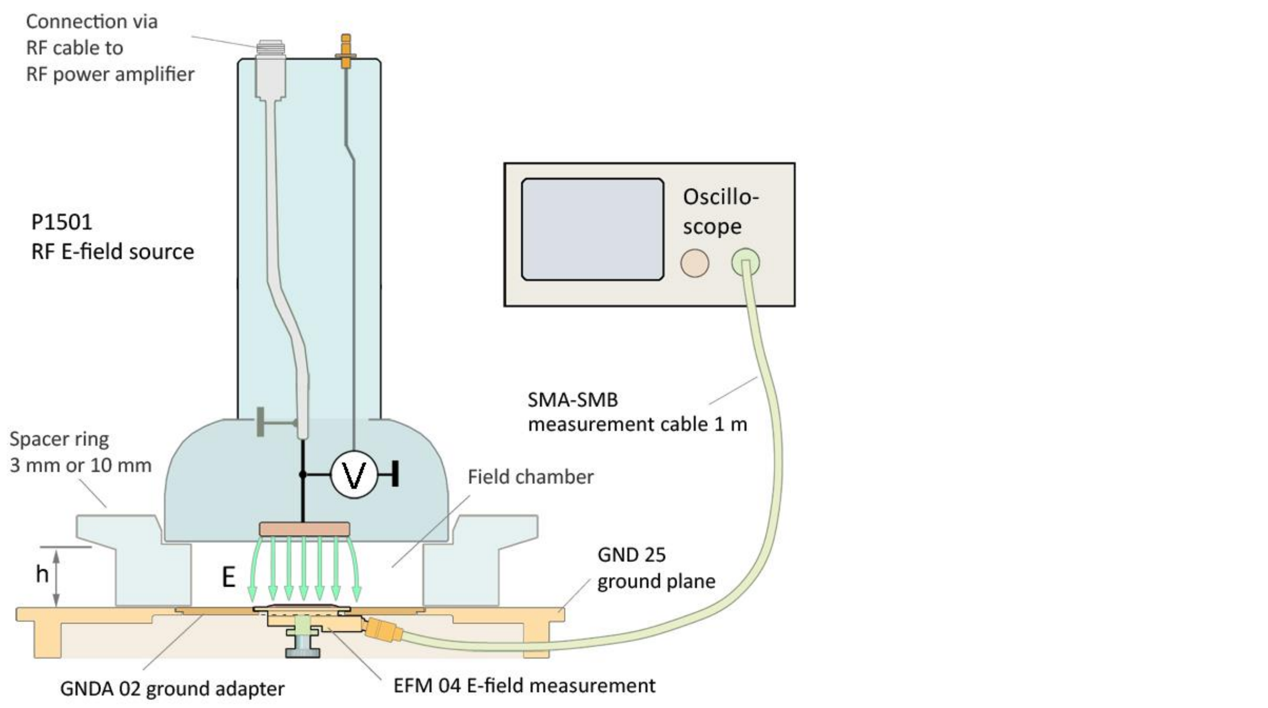

Figure 41 Measurement of the electric field of the ***P1501*** field source with the ***EFM 04*** E-field meter.

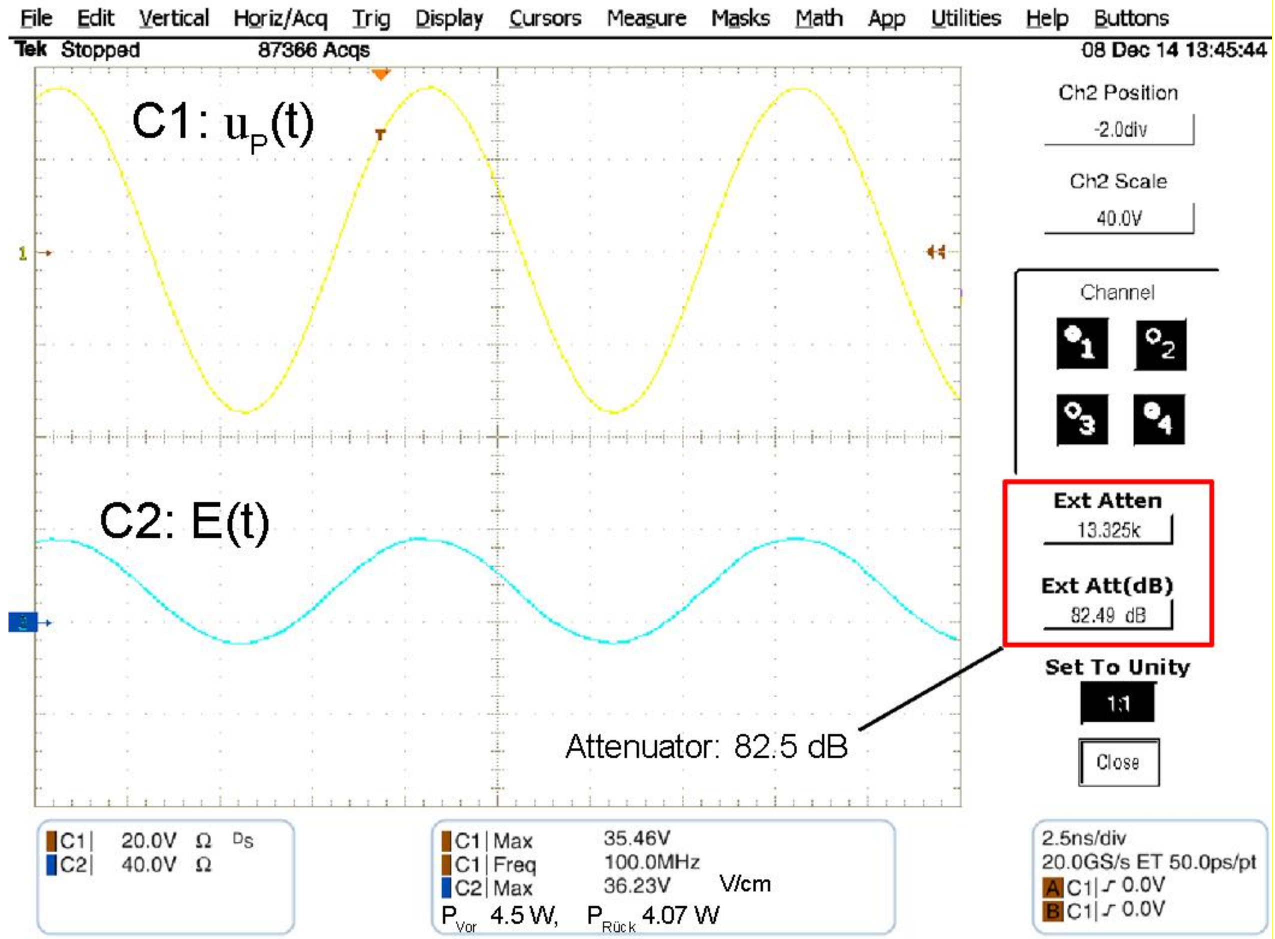

Figure 42 E(t) and u_P(t) of the ***P1501*** field source at P_{Vor} 4.535 W, $P_{Rück}$ 4.07 W.

The signal delay is corrected in the same way as with EPM 02 to ensure in-phase measurements with the oscilloscope.

1.4.6 Measurement of the variation of the electric field dE/dt

The ***EPM 02*** Ė-field meter can be used to measure the variation of dB/dt = Ė(t) over time in the field chamber at the test IC location (**Figure 44**). The electric field strength E(t) in the field chamber is based on the voltage $u_P(t)$ and the distance h (spacer ring) between the electrode and ground. dE/dt is based on the variation of $u_P(t)$ over time (**Figure 43**).

$dE/dt = \dot{E}(t) = d(u_P(t)/h)/dt$ absolute value in the complex case → $\dot{E} = (\omega/h) \cdot U_P$ Eqn 27

The displacement current per unit length $i'_1(t)$ [A/mm²] (**Figure 49**) which is imposed on the test IC results from:

$i'_1(t) = \varepsilon \cdot dE/dt = \varepsilon \cdot \dot{E}(t) = dD/dt$ Eqn 28

where $\varepsilon = \varepsilon_r \cdot 8.85\ 10^{-12}$ As/Vm is the dielectric constant, and $D = \varepsilon \cdot E$ is the electrical space charge density [A/mm² s] at which the area A_{Pad}, for example, is occupied (**Figure 39**).

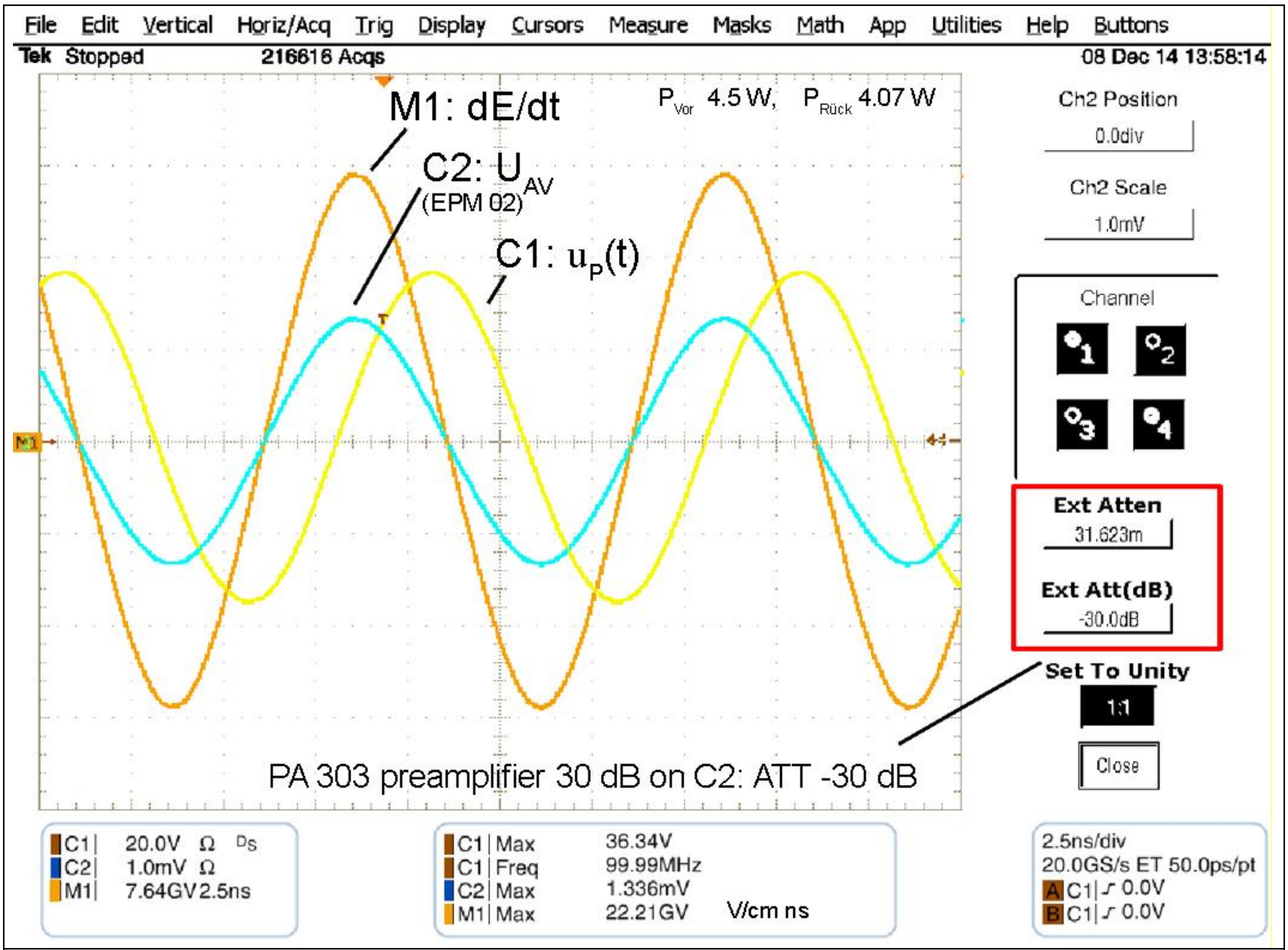

Figure 43 dE/dt and $u_P(t)$ of the ***P1501*** field source. The output signal of the ***EPM 02*** dE/dt meter is amplified by 30 dB with the ***PA 303*** preamplifier. This is taken into account in the vertical menu C2.

The Ė-field meter is inserted into the ground adapter instead of the test IC. The ***EPM 02*** Ė-field meter fits into the ***GNDA 02*** ground adapter and has to be inserted into the ***GND 25***[17] ground plane for the measurement.

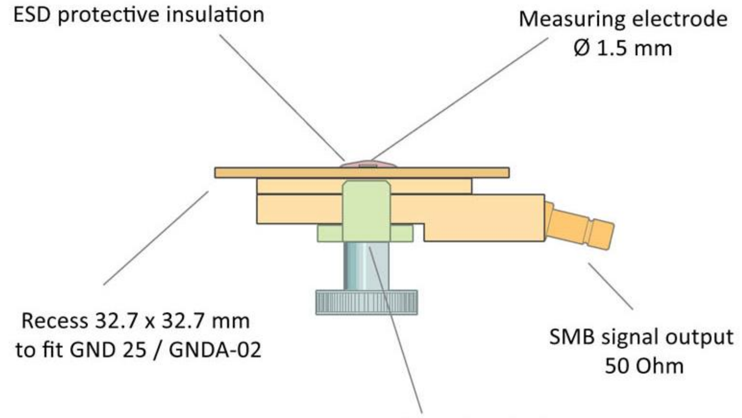

Figure 44 *EPM 02* E-field meter to measure the electric field.

The SMB output of the ***EPM 02*** Ė-field meter is connected to the input of the oscilloscope via the 50 Ohm SMA-SMB measuring cable (**Figure 41**). The measurement output is matched to 50 Ohm. The oscilloscope's input has to be set to 50 Ohm to obtain correct values during the measurement. The Ė-field meter supplies the voltage $u_{AV}(t)$ at the signal output. The voltage $u_{AV}(t)$ is proportional to the variation of the electric field strength Ė(t) over time at the ***EPM 02*** measuring electrode. The voltage $u_{AV}(t)$ is converted to the variation of the electric field strength Ė(t) over time with a correction factor of the ***EPM 02*** (attenuator value).
The attenuator value shown on the Ė-field meter is entered into the channel settings or vertical menu of the oscilloscope. The following value may be shown: ATT 264.4 dB, E[kV/cm ns] where 264.4 dB corresponds to 20 log 264.4 = $1.6599\ 10^{12}$.
The attenuator value is used to display the variation of the electric field strength over time on the oscilloscope in V/cm ns (GV/cm s). Attenuator values up to 200 dB (x 10^{10}) can usually be set in the vertical menu or channel settings of the oscilloscope. It is thus useful to set the attenuator value to 0 dB (x 1) in the channel settings and to calculate Ė(t) on a mathematical channel (**Figure 45**). $u_{AV}(t)$ was measured on the oscilloscope channel C2 at an ATT setting of 0 dB in **Figure 43**. The mathematical channel M2 is used for calculation ($1.6599\ 10^{12} \cdot$ C2) (**Figure 45**).

[17] ***GNDA 02*** ground adapter and ***GND 25*** ground plane are included in the ***ICE1*** test environment. www.langer-emv.de The test board is described in the "***IC test instructions***“, mail@langer-emv.de.

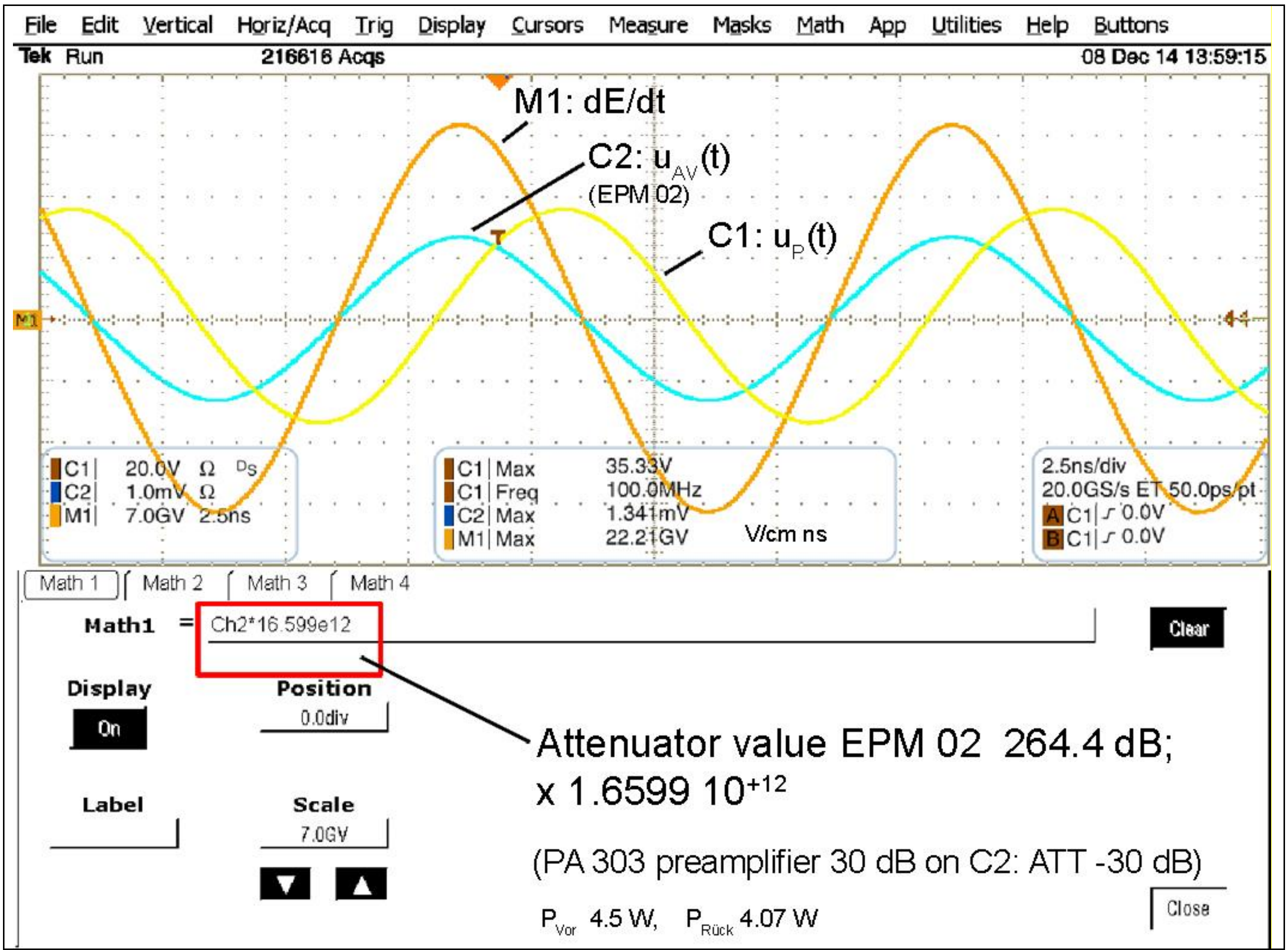

Figure 45 Setting of the mathematical channel to calculate $\dot{E}(t)$ from C2. The attenuator of C2 was set to 0 dB (x1).

The attenuator value can be converted to dD/dt with **Eqn 28** or with ε to the displacement current per unit length i'_1.

Make sure that the measurement signal does not exceed the oscilloscope's maximum permissible input voltage. An external attenuator should be used if necessary. A preamplifier can be used if the signal is too weak. (***PA 303***, 30dB, Langer EMV-Technik GmbH)

If a phase relationship is to be established between the probe voltage $u_P(t)$ and E in the oscilloscope, the propagation delay of the field source's measuring branch and the ***EPM 02*** has to be entered as Deskew. Begin by entering the propagation delay of the field source's measuring branch (E-field to AV output of the voltage divider) (**Figure 46, Table 9**).

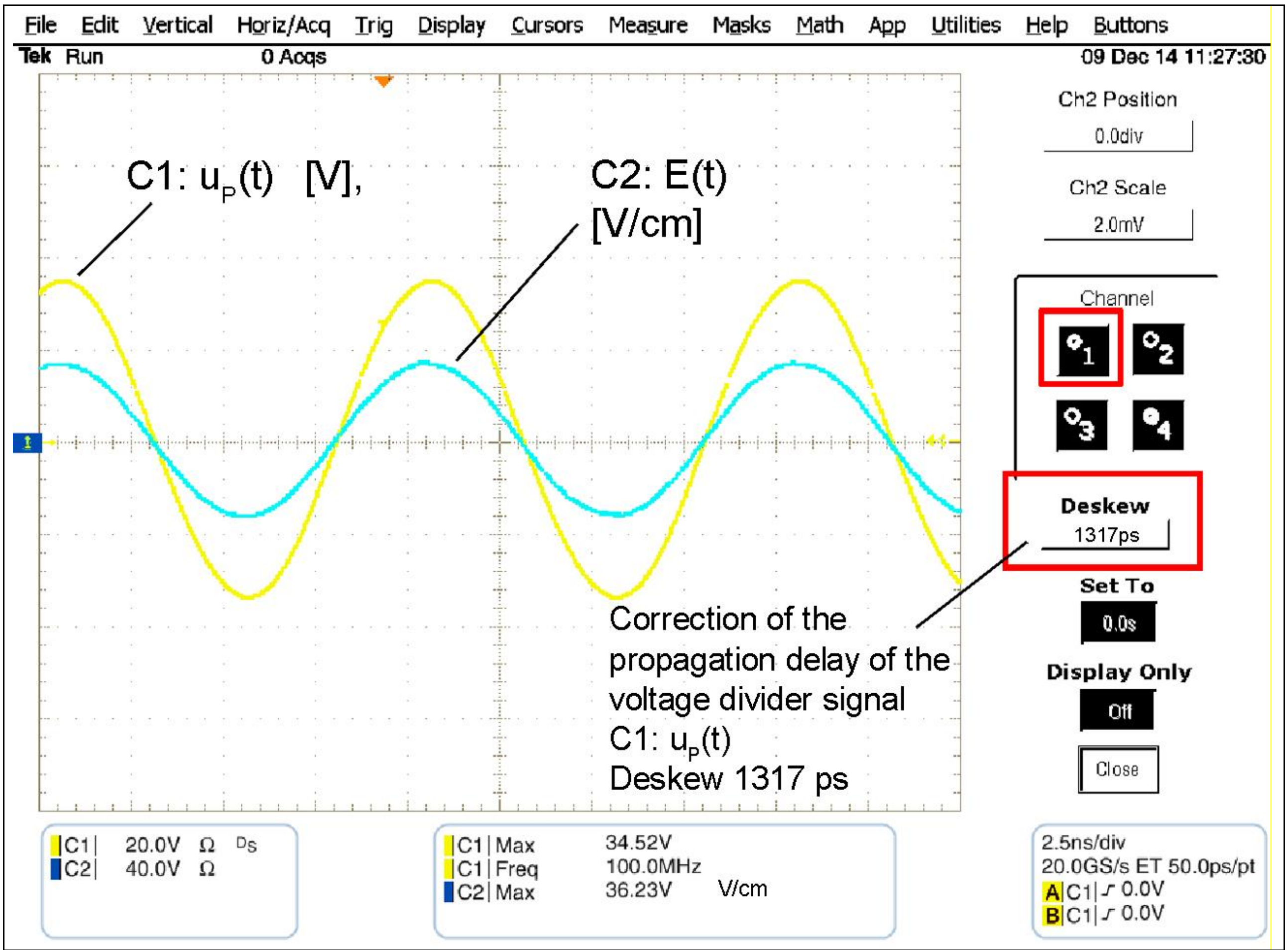

Figure 46 Propagation delays of the measuring branch from the E-field of the field source to the U_{AV} output of the voltage divider have to be entered on the oscilloscope as Deskew.

Then enter the propagation delay of the EPM 02 (**Table 10**) in the corresponding measuring channel of the oscilloscope. This is channel C2 in this case. The procedure is analogous to channel C1. A propagation delay of 117 ps (**Table 10**) has already been taken into account for ***BPM 02*** in **Figure 46**. The phase relations are thus shown correctly on the oscilloscope. This is clearly recognizable through the phase quadrature of dE/dt(t) relative to $u_P(t)$ (**Figure 48**) and the phase coincidence between E(t) and $u_P(t)$ **Figure 46**.

An additional signal delay of 440 ps will occur if the ***PA 303*** preamplifier is inserted in a measuring channel. Make sure that this delay is taken into account in the oscilloscope settings for in-phase measurements. It may be necessary to match the settings in practice to ensure the correct phase relation for every measurement set-up.

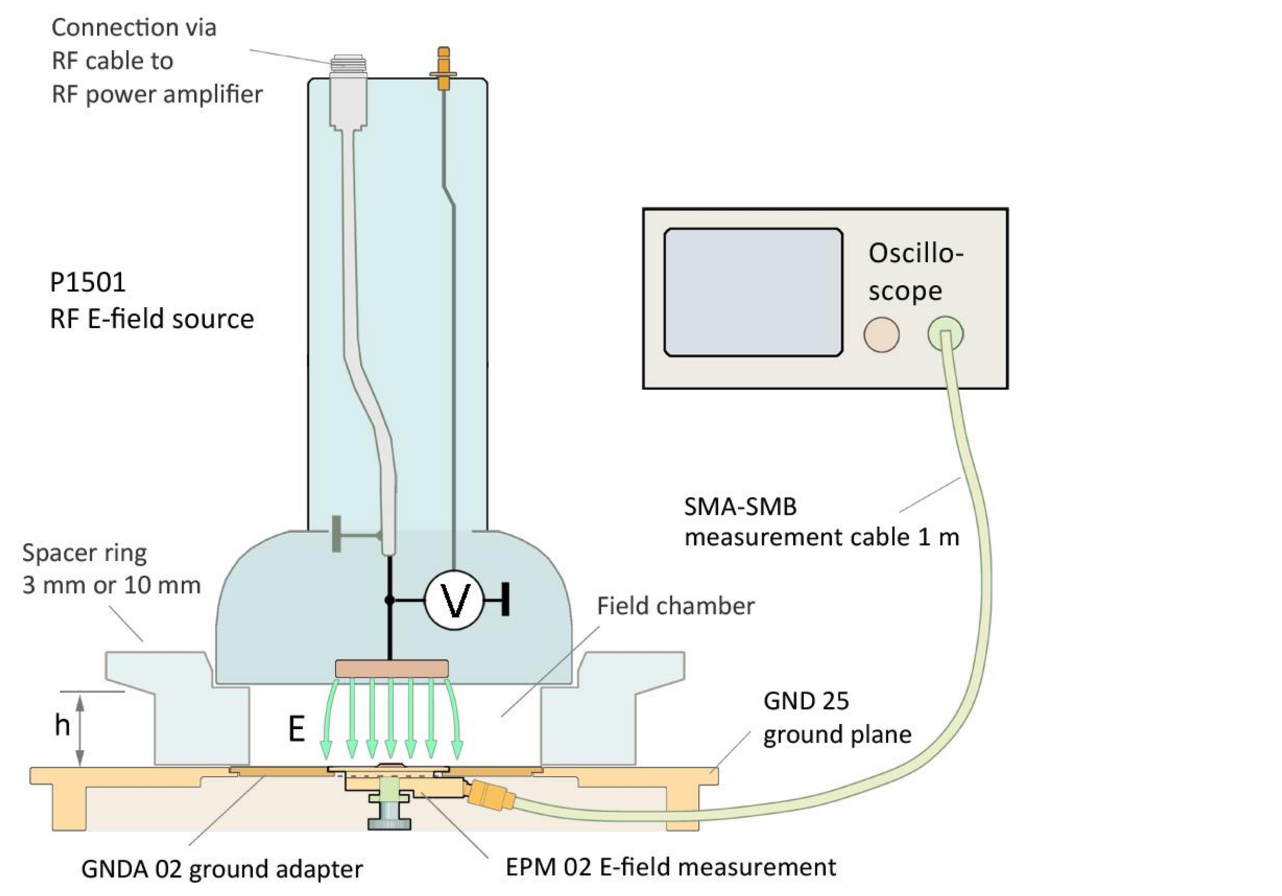

Figure 47 Measuring the variation of the electric field of the ***P1501*** field source with the ***EPM 02*** Ė-field meter.

The Ė variation over time can be converted to the electric field strength E(t) by integration.

$E(t) = \int \dot{E}(t)\,dt + C$ in the complex case → $E = (1/\omega)\,\dot{E}$ (+C) Eqn 29

where C is the constant of integration. The integration can be performed in the oscilloscope (**Figure 48**). The measurement signal $u_{AV}(t)$ (C2) is converted to Ė(t) with the respective attenuator value (**Figure 45**) in the oscilloscope. This is performed here on the mathematical channel M2. The unit of measurement for Ė(t) is then kV/cm ns. Ė(t) from the mathematical channel M2 is entered into the mathematical channel M4. The result of the integration is the field strength E(t) in the unit of measurement kV/cm (**Figure 48**). A conversion to V/m can be performed with x 10^5.

The value of the constant of integration C has to be entered in the equation of the oscilloscope by hand. The procedure has been described in more detail for the determination of the flux density B in chapter **1.2.8**.

The final value of the constant of integration is determined by iteration. 0, for example, can be used as the initial value. The field strength calculated by integration must be proportional to the known variation of $u_P(t)$ over time. **Figure 43** and **Figure 45** show $u_P(t)$ as a function of time. The value of the constant of integration has to be adjusted gradually by hand until the variation of E(t) is proportional to the variation of $u_P(t)$. If the value of the constant of integration C is too small, the measured curve E(t) drops relative to $u_P(t)$ (shown in **Figure 20** for the B field). The constant of integration C then has to be increased. If, however, the measured curve rises relative to u_P, the value of the constant of integration C is too large (shown for B field in **Figure 21**) and then has to be reduced by hand.

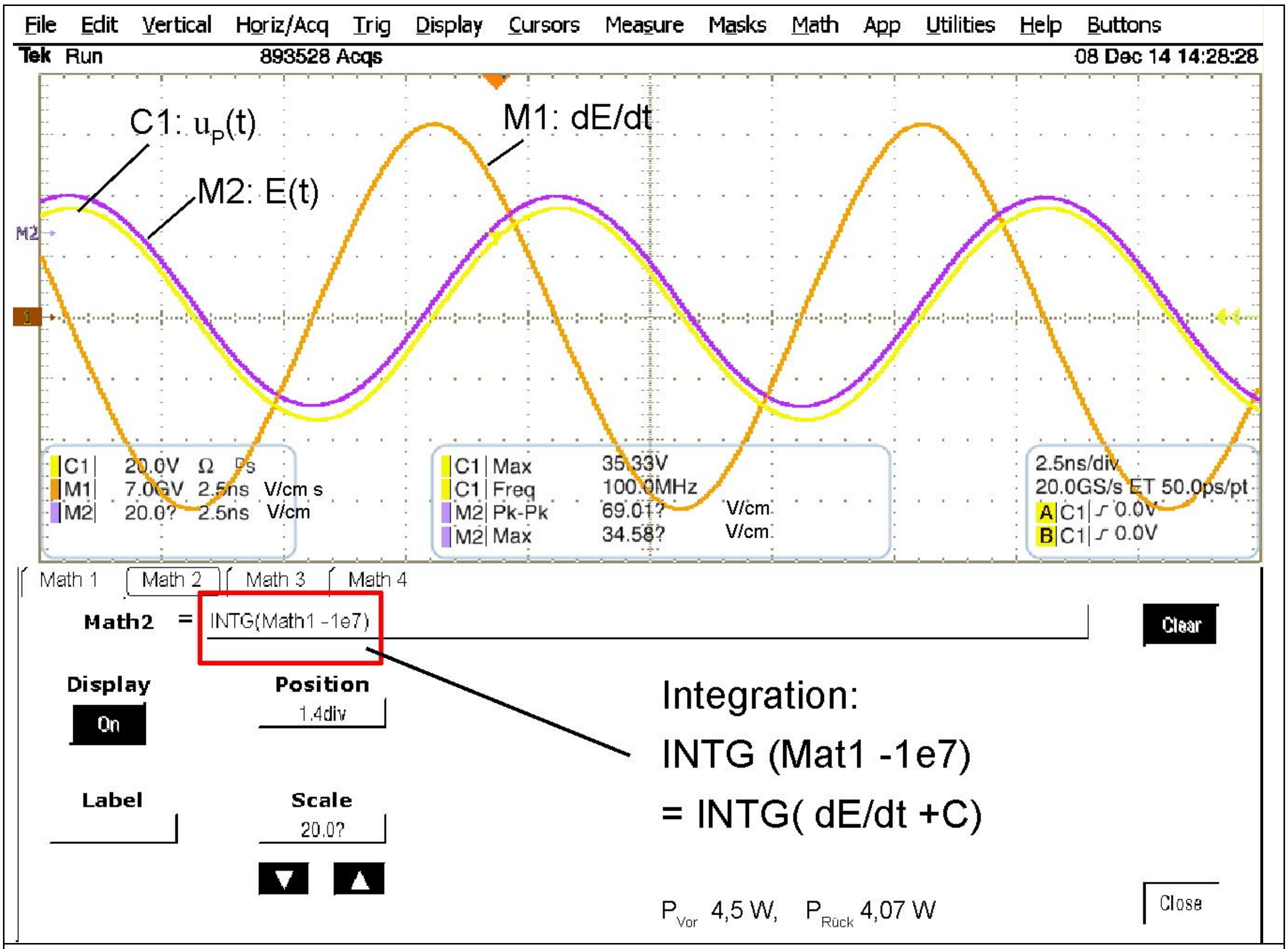

Figure 48 Integration over dE/dt (mathematical channel M2) results in the field strength E(t) [V/cm]. The curve E(t) coincides with that of $u_P(t)$ at a spacer ring height of h = 10 mm.

If $\dot{E}$ is measured logarithmically (in dB) with a spectrum analyser, E can be integrated in the following way:

$E = \dot{E} - 20 \log \omega$ Eqn 30

The measurement signal can be corrected with 20 log ω by means of the ***CS-ESA***[18] software.

[18] The ***CS-ESA*** software from Langer EMV-Technik GmbH has been developed for the clear and comparable recording, documentation and analysis of a spectrum analyser's measurement curves. www.langer-emv.de.

1.4.7 Mechanism of capacitive coupling from the *P1501* field source to the test IC

There are two main types of capacitive coupling from the electrode of the field source to the pads of the test IC (**Figure 39**). The types of coupling are derived from the field equivalent circuit of the electrode of the ***P1501*** field source and the pad (**Figure 49**).

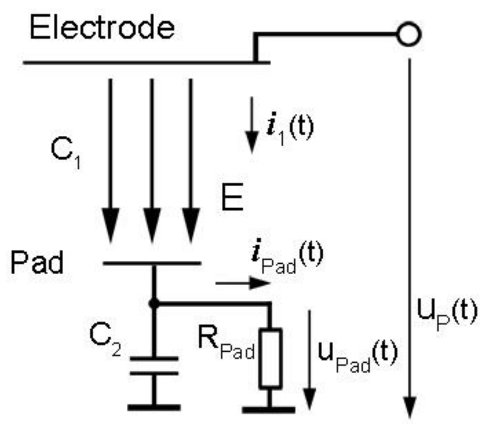

Figure 49 Field equivalent circuit of the electrode of the ***P1501*** field source and the pad.

The voltage $u_P(t)$ **Figure 49** generates an electric field E(t) on the electrode of the ***P1501*** field source The pad and the electrode of the field source form a plate capacitor. The field E(t) in the plate capacitor (electrode-pad) couples a current $i_1(t)$ to the pad. This current is a capacitive current. The associated capacitance C_1 is the capacitance of the plate capacitor (pad-electrode).

$I_1(t) = C_1 \cdot du_P/dt \quad (\text{at } u_P \approx u_{C1})$ Eqn 31

The current $i_1(t)$ can be normalised to the area A_{Pad} [mm²] of the plate capacitor C_1.

$I_1'(t) = i_1(t)/A_{Pad} = (C_1/A_{Pad})\, du_P/dt \quad = C_1' \cdot du_P/dt \quad = \varepsilon\, dE/dt = dD/dt$ Eqn 32

The specific current that flows into the test IC has the unit of measurement A/mm², **Table 8**.

The pad has an inherent capacitance C_2 to ground. The field equivalent circuit (**Figure 49**) can be transferred to a lumped-element capacitive divider (**Figure 50**).

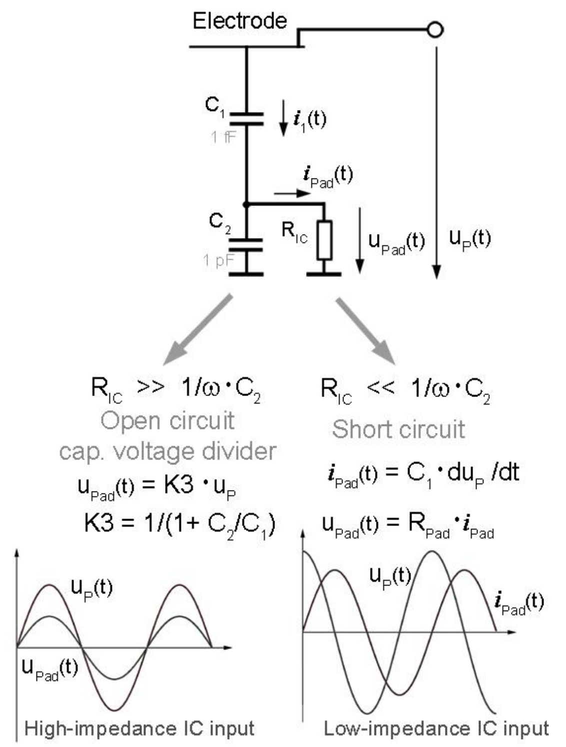

Figure 50 Equivalent circuit of the capacitive divider; main types of capacitive coupling by case distinction.

Determining the main types of capacitive coupling by case distinction:

1. Voltage coupling

The circuit operates like a capacitive voltage divider under open-circuit conditions if R_{Pad} >> $1/\omega$ C_2. R_{Pad} can be ignored in this case. The voltage $u_P(t)$ is divided by the divider at the ratio C_1/C_2. The factor is approximately 1000 in the example (**Figure 50**). Approximately 1/1000 of $u_P(t)$ is present at C_2. This voltage is applied to the test IC. It follows the capacitive divider independent of the frequency. The voltages are divided independent of the frequency at the ratio C_1/C_2. This is why the variation over time of the test IC voltage is identical to that of the voltage $u_P(t)$ on the electrode of the field source, i.e. an in-phase sine wave. The peak value of $u_P(t)$ is attenuated by the coupling factor K3 (**Figure 50**).

R_{Pad} must be in the range of 10 kOhm to transfer all frequencies up to 1 GHz. This requirement is met for pads with respective pull-up and pull-down resistances, at quartz oscillators and open pins.

2. Current coupling

The circuit operates under short-circuit conditions if R_{Pad} << $1/\omega$ C_2. The capacitance C_2 is short-circuited by R_{Pad}. The current $i_{Pad}(t) = C_1 \cdot du_P/dt$ differentiated from $u_P(t)$ is discharged via $R_{Pad.}$. It generates the voltage $u_{Pad}(t)$ at R_{Pad}. Current components with higher frequencies generate a higher voltage. The voltage $u_{Pad}(t)$ may interfere with signals of the test-IC. The greater R_{Pad} is, or the higher the frequency of the field source's probe voltage $u_P(t)$ is, the larger the voltage $u_{Pad}(t)$ will be.
The voltage $u_P(t)$ (voltage at the electrode) is differentiated by the capacitor C_1 (**Figure 50**).
The higher the frequency of $u_P(t)$ (frequency of the signal generator, **Figure 3**) is, the higher the current $i_{Pad}(t)$ that is coupled to the pad will be.

1.4.8 Disturbance voltage transfer to the test IC

The voltage $u_P(t)$ divides with the capacitive divider C1/C2 into $u_{Pad}(t)$. The effective values are used in the following calculations:

$u_{Pad}(t) = C_1/C_2 \cdot U_P = K3 \cdot u_P(t)$ Eqn 33

Assuming $C_2 >> C_1$, the equation for the coupling factor K3 (**Figure 50**) of the capacitive voltage divider can be simplified:

$K3 = C_1/C_2$ Eqn 34

Please note that the capacitance per unit length of the IC pin to ground (test board) alone is not the IC pin's total capacitance. This capacitance per unit length is around 0.2 pF/mm² for the circuit board material FR4 with a layer distance of 0.2 mm. There is a larger capacitance share at the line networks in the layout of the test board and at the line networks in the test IC (protective diodes). C_2 contains this total capacitance. It only depends slightly on the area of the (abstract) pad to ground. Normalisation of C_2 to the area of the (abstract) pad is thus not useful.
However, the capacitance C_1 can be normalized to the pad area A_{Pad}. The normalised capacitance C_1 is designated as capacitance per unit length C_1'.

$C_1' = C_1/A_{Pad}$ Eqn 35

The capacitance per unit length C_1' is a field source constant. It results from:

$C1' = \varepsilon_0 \varepsilon_r / h$ Eqn 36

It is listed in **Table 7** for the height h of 3 mm and 10 mm. The pad area A_{Pad}, i.e. the total metallic area of an IC network (plate capacitor) that is effective for the electric field E, has to be used for calculations.

The constant K3 can be estimated. The total capacitance C_2 of a pad should be 5 pF. The area of the pad that is effective for the electric field E of 4 mm² generates a capacitance C1 of 5 fF together with the capacitance per unit length C_1' of 1.35 fF/mm². These two capacitance values generate a coupling factor of $K3 = C_1/C_2$ of approximately 1000. This means that a probe voltage U_P = 35 V (P_{vor} approx. 5 W) at the electrode of the field source is divided to approximately 0.035 V at the IC pin. This low voltage will hardly be able to interfere with digital systems but analogue systems may become a victim of interference.

1.4.9 Disturbance current transfer to the test IC

The electrode of the ***P1501*** field source is coupled capacitively to the pad of the test IC.
In the event that $R_{Pad} << 1/\omega C_2$, R_{Pad} short-circuits the capacitance C_2 so that the following applies:

$i_{Pad}(t) = C_1 \cdot du_P/dt$ in the complex case → $i_{Pad} = C_1 \cdot \omega \cdot U_P$ Eqn 37

where the capacitance C_1 is the capacitive coupling between the electrode and the pad of the test IC.
C_1 can be calculated from the specific capacitance C_1' and the pad area A_{Pad}.

$C_1 = C_1' \cdot A_{Pad}$ Eqn 38

Eqn 39 thus results from **Eqn 37**:

$i_{Pad}(t) = C_1' \cdot A_{Pad} \cdot du_P\ dt$ in the complex case→ $i_{Pad} = C_1' \cdot A_{Pad} \cdot \omega \cdot U_P$ Eqn 39

The current per unit length is calculated with the following equation:

$i_{Pad}'(t) = C_1' \cdot\cdot du_P/dt$ in the complex case→ $i_{Pad}' = C_1' \cdot \omega \cdot U_P$ Eqn 40

The cross-sections of the inner and outer continuous metallic coupling areas A_{Pad} of the test IC can be determined on the basis of its design. The current $i_{Pad}(t)$ that is coupled in can be calculated with the value A_{Pad}, the capacitance per unit length C_1' and the voltage du_P/dt differential.
The current $i_{Pad}(t)$ will flow through the resistance R_{Pad} (**Figure 39**). This resistance corresponds to the total resistance of the current path from the coupling area A_{Pad} to the ground plane **Figure 49**. It may include driver resistances outside the test IC, pull-up or pull-down resistances. The values are between a few 10 Ohm and 10 kOhm. It may even be MOhm in special cases (quartz crystal, open pins). **Figure 51** shows the effect of these different resistances at a field strength of Ê = 35 V/cm or a forward power P_{vor} = 5.4 W and a pad area A_{Pad} of 7 mm².

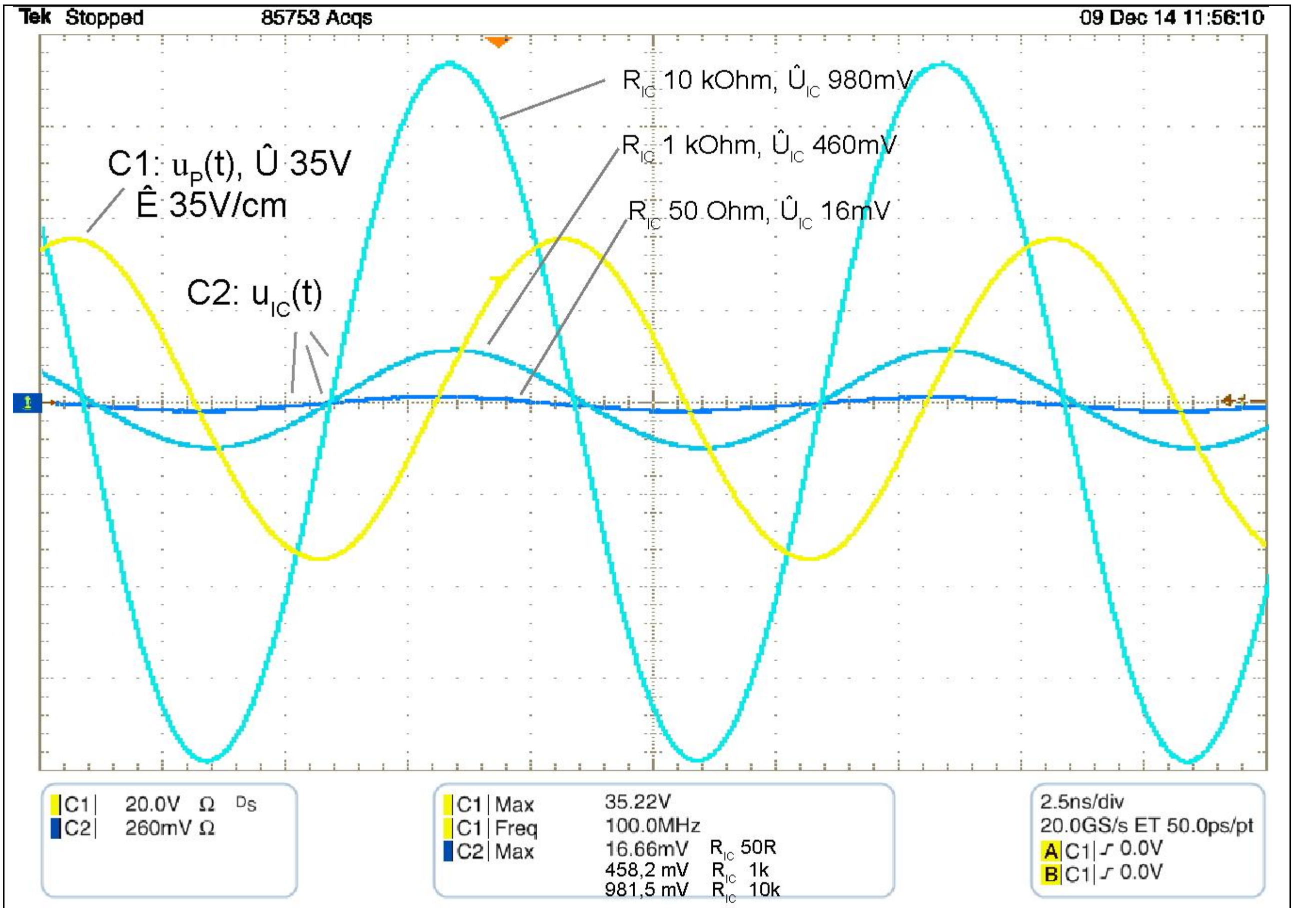

Figure 51 Voltage variation $u_{Pad}(t)$ over time at different resistances R_{Pad} of an IC pin with E-field coupling (spacer ring 10 mm).

The higher the value of the resistance R_{Pad} is, the higher the voltage which is coupled to the IC will be. The R_{Pad} values start to become critical at approx. 1 kOhm. Disturbance voltages with a higher frequency generate more voltage $u_{Pad}(t)$.

Capacitive coupling to the test IC which is described here may be used as a starting point for simulations.

1.4.10 Harmonics

The power amplifier can generate harmonics depending on the frequency and modulation. The harmonics for the electric field are based on similar interactions as the harmonics for the magnetic field, see chapter **1.2.13**.

1.4.11 Frequency response of the *P1501* field source

Figure 52 shows the frequency response K1(f) of the probe voltage U_P relative to the field strength E. The transfer function drops by approx. 3 dB in the range up to 1 GHz. These deviations can be compensated by voltage measurements and readjustment of the power amplifier.
The voltage $u_P(t)$ may have harmonics (produced in the power amplifier). These harmonics may be outside the operating range in a frequency spectrum of > 1 GHz. They are converted to electric field shares with the coupling factor K1(f) which is also effective outside the field source's operating range **Eqn 25**. If, for example, the frequency response K1(f) of the field source does not remain constant in this area but rises by 6 dB, the peak value of the electric field harmonics will double. The interference ability of the field source thus increases. It has to be ensured that there is no substantial increase in frequency response K1(f) in the range > 1 GHz.
Figure 53 shows the frequency response up to 3 GHz (shows the third harmonic for a fundamental frequency of 1 GHz). There is no problem of an additional increase in the interference ability of the field source with harmonics since the frequency response drops by at least 2 dB in the range between 1 GHz and 3 GHz. This drop suppresses harmonics in this range.

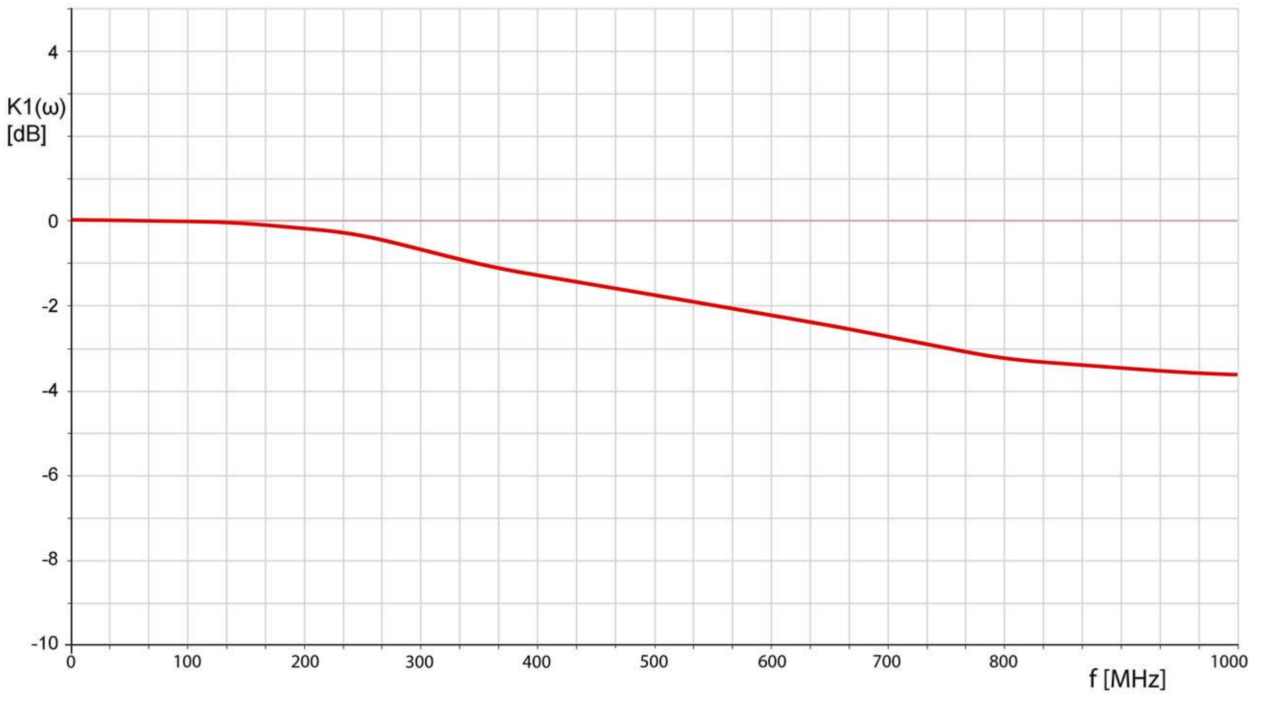

Figure 52 Frequency response of the probe voltage U_P as a function of the electric field strength E in the field chamber.

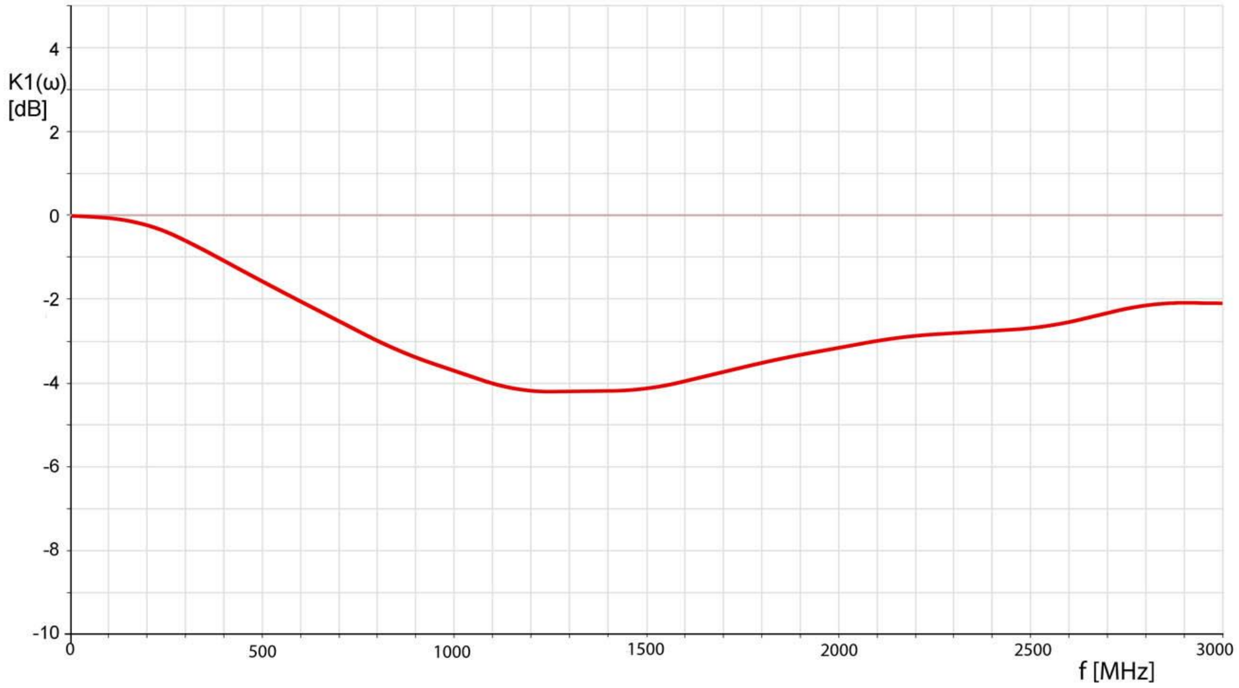

Figure 53 Frequency response of the probe voltage U_P as a function of the electric field strength E in the field chamber up to 3 GHz.

Figure 54 shows the frequency response of the measurement voltage divider K4(f) up to 1 GHz. The correction value 60 dB is usually set at the oscilloscope. If the voltage values are not precise enough, the corresponding frequency value given in **Figure 54** has to be inverted before being entered. The frequency response of the shunt is similar to that of the frequency response K1(f). **Figure 54** shows that the frequency response of the measurement voltage divider does not drop by more than 1 dB up to 1 GHz and **Figure 55** shows that the field source can be used up to a frequency of 1.7 GHz. The electric field strength is determined with the following equation at a spacer height of 10 mm:

$E10\ mm = u_{AV}(f) * 1/K4(f)$ Eqn 41

The electric field strength is determined with the following equation at a spacer height of 3 mm:

$E3\ mm = 10/3 * u_{AV}(f) * 1/K4(f)$ Eqn 42

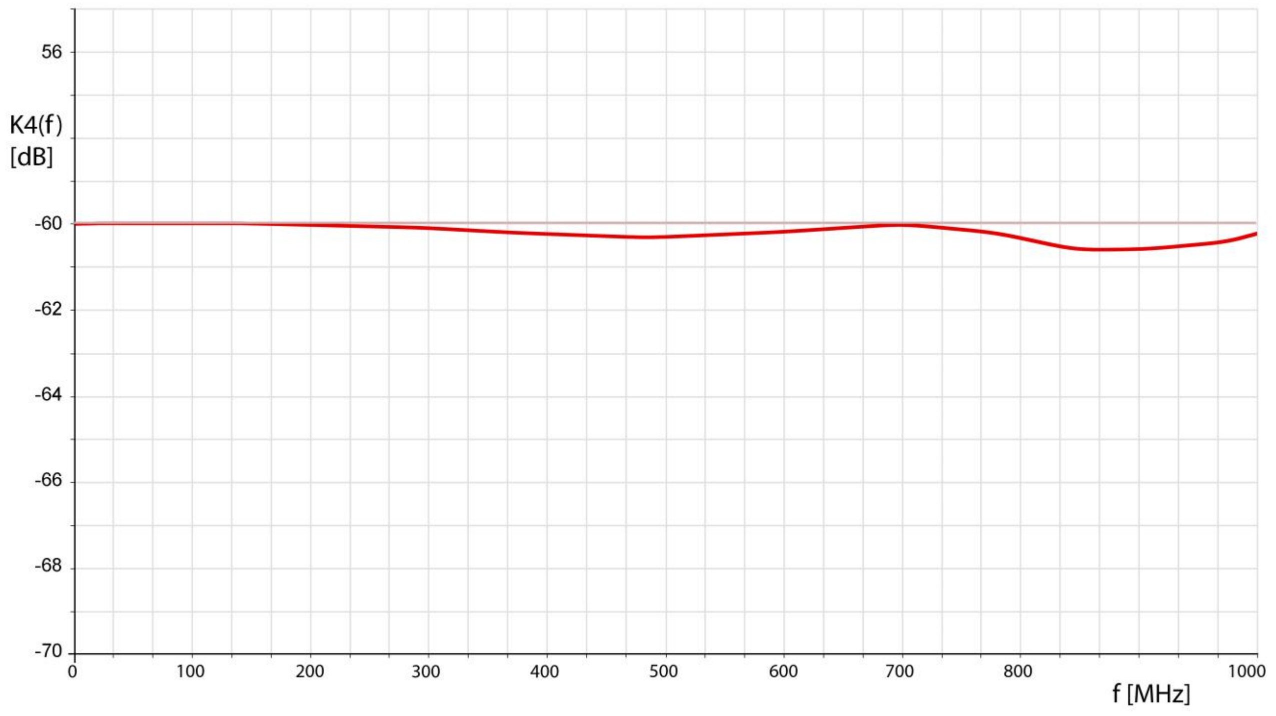

Figure 54 Frequency response K4(f) of the measurement voltage divider of the electric field E relative to the output voltage of the measurement divider for a distance spacer height of h=10 mm.

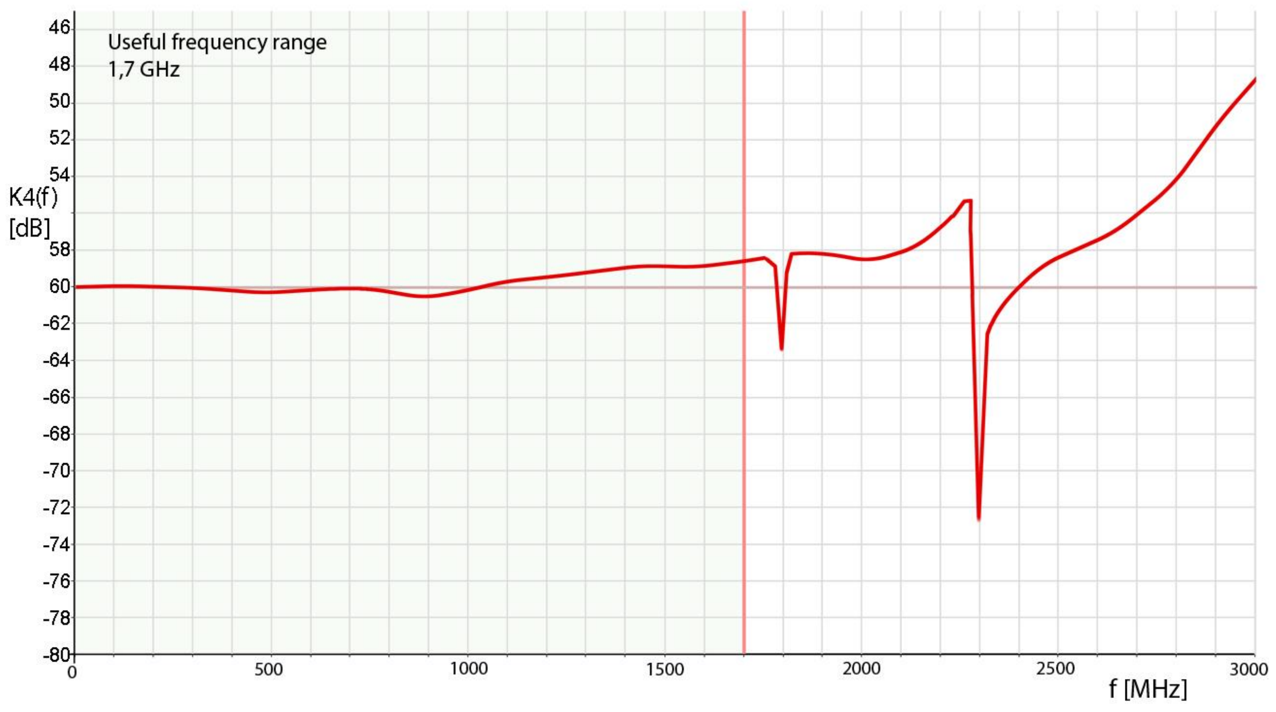

Figure 55 Frequency response K4(f) of the measurement voltage divider of the electric field E relative to the output voltage of the measurement divider for a distance spacer height of h=10 mm up to 3 GHz.

1.5 Set-up of the test bench / system set-up

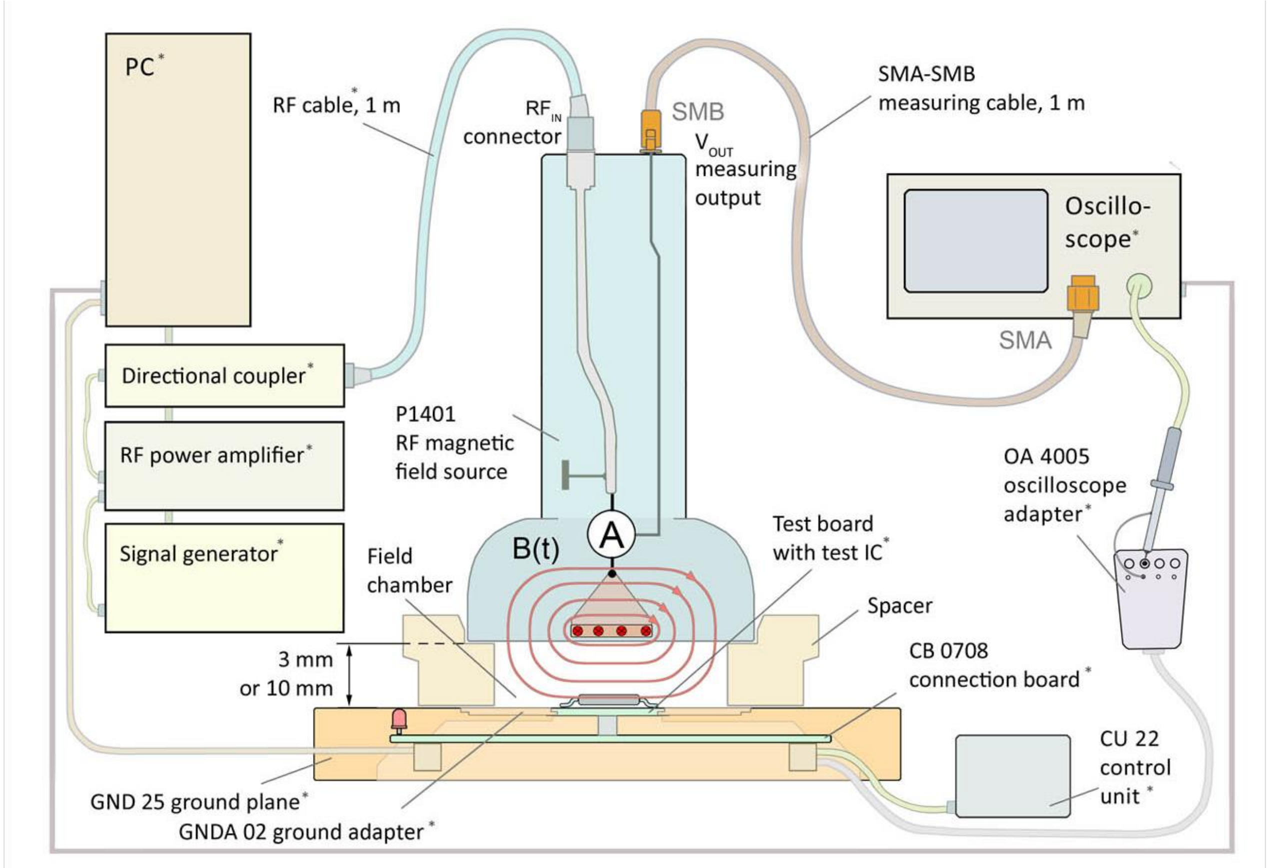

Figure 56 ***P1501*** field source in the ***ICE1*** test environment.

Components marked * are not included in the scope of delivery of the "1 GHz RF power field coupling" probe set.

All field sources included in the "1 GHz RF power field coupling" probe set are connected in the same way and require the same ***ICE1*** test environment (www.langer-emv.de). **Components marked** * are not included in the scope of delivery of the "1 GHz RF power field coupling" probe set. **Figure 56** shows the set-up of the test bench with the ***ICE1*** IC test environment (**Table 1**) and the ***P1401*** field source. The power amplifier generates the RF power current. The forward and reverse power is measured with the directional coupler. The power amplifier, directional coupler and field source are connected with a corresponding RF cable. The test bench can be controlled at the devices by hand or from a PC with the ***ProbeControl*** control and monitoring software (www.langer-emv.de) via an interface. Manufacturing the test board is described in the ***Guide line IC EFT immunity***.

The test IC is mounted on a test board.[19] The test board is inserted into the ***GNDA 02*** ground adapter which is inserted into the ***GND 25*** ground plane. The test board is connected to the ***CB 0708*** connection board via connectors (**Figure 56**) (user manual of the ***ICE1*** IC test environment[20]).

Two different spacer rings are included in the scope of delivery. The spacer rings have a height of 3 mm and 10 mm respectively. The height of the field source above the ground plane (and thus above the test IC) can be defined by selecting the respective spacer ring. A height of 10 mm is the preferential setting.

[19] ***IC test instruction manual***, mail@langer-emv.de

[20] The ***GNDA 02*** ground adapter, ***GND 25*** ground plane and ***CB 0708*** connection board are included in the ***ICE1*** IC test environment. www.langer-emv.de The test board is described in the „***IC test instruction manual***“, mail@langer-emv.de.

The 3 mm spacer ring can be used if the maximum field strength (maximum forward power) is not sufficient to interfere with the test IC when using the 10 mm spacer ring. The electrode or electric conductor is closer to the test IC if the 3 mm spacer ring is used. The interference effect is thus increased at the same forward power. The proximity to the test IC causes a stronger field distortion with 3 mm than with 10 mm. The measuring accuracy is thus higher when using the 10 mm spacer ring.
When using the 3 mm instead of the 10 mm spacer, the magnetic flux density is increased by the factor 2 and the electric field strength is increased by the factor 3 (ignoring the test IC interaction).
The chosen spacer ring is mounted on the ***GND 25*** ground plane (**Figure 56**). The ***P1401*** or ***P1501*** field source is then inserted into the upper recess of the spacer ring. The ***P1401*** magnetic field source can be rotated in the spacer ring by 360°. The orientation of the emitted magnetic field can thus be adjusted gradually to penetrate all loops of the test IC (Chapter **1.2.5**).
The ***OA 4005***[21] oscilloscope adapter and the ***CB 0708*** connection board can be used to evaluate signals from the test IC.
The ***CB 0708*** connection board and the ***CU 22***[22] control unit are used to control the test IC.
The ***ICE1*** user manual provides information on how to use and wire these components. **Figure 57** shows the set-up of a practical test bench.

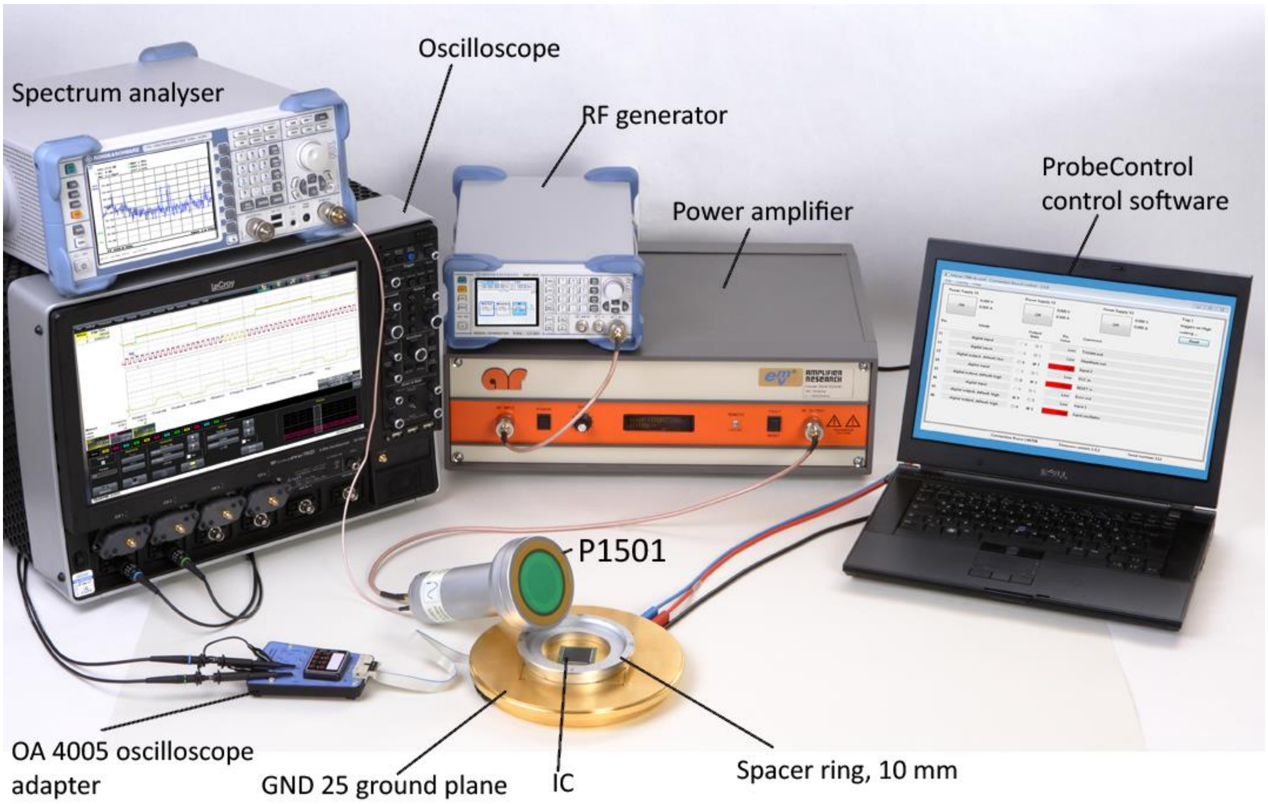

Figure 57 Test set-up with the 1 GHz RF power field coupling probe set, ***ICE1*** IC test environment and other devices (simplified set-up without directional coupler).

[21] The ***OA 4005*** oscilloscope adapter is included in the ***ICE1*** IC test environment. www.langer-emv.de
[22] ***CU 22*** mail@langer-emv.de

The devices listed in the table are described in their respective instruction manuals:

Task	**Instruction manual**
• Instructions for the development of the test board • Test process	IC test instruction manual (Langer EMV-Technik GmbH)
• GND 25 ground plane • CB 0708 connection board • OA 4005 oscilloscope adapter • Monitoring and controlling the test IC • CU 22 control unit	ICE1 user manual
• Power amplifier • Directional coupler • Signal generator • Oscilloscope • PC	Operating instructions of the manufacturer
Table 1	

1.6 Performance of the test

The test bench can be used in two ways:

1. **Manual control of the test bench**

The signal generator and power amplifier are used to control the test bench. The signal parameters are set at the signal generator and power amplifier. The devices are set according to the manufacturer's operating instructions either on the control elements of the devices or on the PC via remote control.

2. **Automated or semi-automated test bench**

The test bench PC must allow an evaluation of the monitoring signals of the test IC. The sources of the monitoring signals are the oscilloscope in conjunction with the ***OA 4005*** oscilloscope adapter and the ***CB 0708*** connection board or proprietary solutions of the user.
Solutions for an automated or semi-automated test bench with the ***ProbeControl*** monitoring and control software are available (advice from Langer EMV-Technik GmbH, mail@langer-emv.de).

1.6.1 Test procedure

The level and frequency of the disturbance is usually increased gradually in the course of the test.
The level of each frequency is gradually increased, starting from a defined minimum value. The level is gradually increased until malfunctions occur (monitoring signals) or the defined maximum value is reached. The frequency is then increased, once again starting from the defined minimum level value.
RF power coupling usually has to be stopped if the monitoring signals indicate functional faults in the test IC. The level can be further increased until further faults occur in special investigations. The test IC may be destroyed in this case. The risk can be reduced by monitoring (***CB 0708*** connection board) or limiting the test IC's power supply. The supply voltage can be interrupted in the case of a fault by an emergency shut-off function. The emergency shut-off can be triggered automatically from the PC or manually via the ***CU 22*** control unit, for example, or a proprietary solution of the user.

The actual value of the magnetic field B of the ***P1401*** magnetic field source is determined at the shunt by a current measurement (B=K1* K4 * U_{AV}). Any deviations from the target value can be corrected by readjustment at the power amplifier. The actual value of the electric field E of the P1502 E-field source is determined through a voltage measurement on the measurement voltage divider (E10mm= U_{AV} * K4). Any deviations from the target value can be corrected by readjustment at the power amplifier.
Solutions for an automated or semi-automated test bench with the ***ProbeControl*** monitoring and control software are available (advice from Langer EMV-Technik GmbH, mail@langer-emv.de).
Test procedures are described in the ***IC test instruction manual*** (mail@langer-emv.de).

A disturbance field is generated in the field chamber of the field source when operating the test bench. Make sure that the field chamber is not opened during the test for safety reasons. The field source may only be operated with the field chamber closed by the spacer ring and ground plane.

1.7 Verifying the waveform

The field sources are calibrated by Langer EMV-Technik GmbH.

Chapters **1.2.7** and **1.2.8**, and **1.4.5** and **1.4.6** describe how to verify the waveform.

2 Safety instructions

This product meets the requirements of the following directives of the European Union: 2004/108/EC (EMC directive) and 2006/95/EC (low-voltage directive).
Read and follow the operating instructions and keep them in a safe place for later consultation. The device may only be used by personnel who are qualified in the field of EMC and who are eligible to carry out this work.
When using a product from Langer EMV Technik, please observe the following safety instructions to protect yourself from electric shocks or the risk of injuries and to protect the devices used and the test IC from being destroyed.

The power amplifier used must be stable under open-circuit conditions and short-circuit-proof.

- Observe the operating and safety instructions for all devices used in the set-up.
- Never use any damaged or defective devices.
- Carry out a visual check before using a measurement set-up with a Langer EMV-Technik GmbH product. Replace any damaged connecting cables before starting the product.
- Never leave a product from Langer EMV-Technik unattended whilst this is in operation.
- The Langer EMV-Technik product may only be used for its intended purpose. Any other use is forbidden.
- People with a pace-maker are not allowed to work with this device.
- The test set-up should always be operated via a filtered power supply.
- **Attention! Functional interference emissions (near fields and far fields) may occur when the field source is operated. The user is responsible for taking appropriate precautions to protect all electronic devices used in the course of the tests. In particular, he is responsible for protecting the measuring devices used in the test set-up and all other electronic devices outside the test bench against interference emissions so that their intended function is not impaired.** This can be achieved by:
  - observing an appropriate safety distance,
  - use of shielded or shielding rooms (e.g. ***shielding tent***, www.langer-emv.de)

A disturbance field is generated in the field chamber of the field source when operating the test bench. Make sure that the field chamber is not opened under any circumstances during the test for safety reasons (hazard due to RF). The field source may only be operated with the field chamber closed by the spacer ring and ground plane. The test bench has to be operated in a shielded cabin with lines of more than 8 W.

We cannot assume any liability for damage due to improper use.

- The disturbances that are injected into the modules can destroy the test IC (latch-up) if their intensity is too high. Protect the device under test by:
  - connecting a protective resistor in the IC's incoming power supply
  - increasing the disturbance gradually and stopping when a functional fault occurs,
  - interrupting the power supply to the test IC in the event of a latch-up.

Attention! Make sure that internal functional faults are visible from outside. The test IC may be destroyed due to an increase in the injection intensity if the faults are not visible from outside. Take the following precautions if necessary:

- monitoring representative signals in the test IC
- special test software
- visible reaction of the test IC to inputs (reaction test of the test IC).

We cannot assume any liability for the destruction of test ICs!

3 Warranty

Langer EMV-Technik GmbH will remedy any fault due to defective material or defective manufacture, either by repair or by delivery of replacement, during the statutory warranty period.

This warranty is only granted on condition that:
- the information and instructions in the user manual have been observed.

The warranty will be forfeited if:
- an unauthorized repair is performed on the product,
- the product is modified,
- the product is not used according to its intended purpose.

4 Technical specifications

P1401, P1501 field sources	
Dimensions (height/width/depth)	180 x 95 x 95 mm
Weight P1401 P1501	 750 g 700 g
Frequency range	0 – 1 GHz
P_{vor} Max	100 W
U_P Max	100 V
Time characteristic	Sin CW, AM
Terminating resistor in the RF current path	without

4.1 Characteristics

4.1.1 Characteristics of the *P1401* magnetic field source

4.1.1.1 P1400 magnetic field source family, probe constants

h [mm]	K1 [µT/A] oder [pVs/mm²A]	L_h' [pH/mm²]
3	24.4	24.4
10	12.4	12.4
	$B = K1 \cdot i_p$	$u_{ind} = L_h' \cdot A_{IC} \cdot di_P/dt$ $U_{ind} = L_h' \cdot A_{IC} \cdot \omega \cdot I_P$

Table 2 ***P1401*** magnetic field source, probe constants

4.1.1.2 Disturbances of the ***P1401*** magnetic field source depending on the current (effective values)

P_{vor} [W]	0.1	0.5	1	5	10	20	50	100
U_{VG} [V]	3.2	7.1	10	22.3	31.6	44.7	70.7	100
i_P [A]	0.06	0.14	0.20	0.45	0.63	0.89	1.41	2.0
B [µT] h = 3 mm	1.5	3.5	4.9	10.9	15.4	21.8	34.5	48.8
B [µT] h = 10 mm	0.8	1.8	2.5	5.5	7.8	11.1	17.5	24.8
U_{IC} [V] A_{IC} = 10 mm² h = 10 mm f = 100 MHz	0.005	0.011	0.016	0.035	0.049	0.070	0.11	0.156

Table 3 Disturbances of the ***P1401*** magnetic field source depending on the current

4.1.1.3 Shunt 0.1 Ohm ***P1401***

Bandwidth	1 GHz
Error	approx. 10 %
Attenuator setting	x 20 A/V, 26 dB
Maximum current	2 A
Deskew B relative to U_{AV} shunt measurement output	1154 ps

Table 4 Shunt 0.1 Ohm ***P1401***

4.1.1.4 BPM 02

Bandwidth	3 GHz
Error	approx. 10 %
Attenuator setting	x $1 \cdot 10^6$ T/s V 120 dB
Deskew B relative to U_{AV} BPM 02 measurement output	144 ps

Table 5 ***BPM 02***

4.1.1.5 E-field suppression ***P1401***

	U_F/I_P [V/A]	E_F/I_P [V/cm A] h = 3 mm	E_F/I_P [V/cm A] h = 10 mm
P1401, middle of electric conductor s = 20 mm	26	86	26

Table 6 E-field suppression E_F/I_P of the ***P1401*** field source depending on the supply current I_P, at 1 GHz (**Figure 32**)

4.1.2 Characteristics of the *P1501* E-field source

4.1.2.1 P1500 E-field source family, probe constants

h [mm]	C_1' [f F/mm²]	K1 [1/cm]
3	2.95	3.33
10	0.88	1.0
$U_{Pad} = R_{Pad} \cdot I_{Pad}$	$I_{Pad} = C_1' \cdot A_{Pad} \cdot \omega \cdot U_P$ $I_{Pad}' = C_1' \cdot \omega \cdot U_P$	E [V/cm] = U_p [V] / h [cm] = K1 [1/cm] $\cdot$ U_p [V] / [cm]

Table 7 P1500 E-field sources, probe constants

4.1.2.2 Disturbances of the ***P1501*** E-field source depending on the probe voltage U_P

P_{vor} [W]	0.1	0.5	1	5	10	20	50	100
U_p [kV]	3.2	7.1	10	22.3	31.6	44.7	70.7	100
E [V/cm] h = 3 mm	10.5	23.6	33.3	74.5	105	149	236	333
E [V/cm] h = 10 mm	3.2	7.1	10	22.3	31.6	44.7	70.7	100
I_{Pad}' [mA/mm²] h = 3 mm	0.0059	0.013	0.019	0.041	0.059	0.083	0.13	0.19
I_{Pad}' [mA/mm²] h = 10 mm	0.0018	0.0039	0.0055	0.012	0.018	0.025	0.039	0.055

Table 8 Disturbances of the ***P1501*** E-field source depending on the forward power P_{vor} and probe voltage U_P

4.1.2.3 Voltage divider ***P1501***

Frequency range	0… 1 GHz
Error	+0 %, -10 % (frequency response **Figure 54**)
Maximum divider voltage	100 100 V
Attenuator setting	x 1000 V / V, 60 dB
Deskew E relative to U_{AV} measurement output of ***P1501***	1317 ps

Table 9 Voltage divider ***P1501***

4.1.2.4 EPM 02

Bandwidth	3 GHz
Error	approx. 10 %
Attenuator setting	x $1.6599 \cdot 10^{12}$ T/s V 264 dB
Deskew B relative to U_{AV} measurement output of EPM 02	117 ps

Table 10 ***EPM 02***

5 Scope of delivery

Item	Designation	Type	Qty.
1	RF magnetic field source	P1401	1
2	RF E-field source	P1501	1
3	Spacer ring 3 mm	D70 h03	1
4	Spacer ring 10 mm	D70 h10	1
5	Measurement cable	SMA-SMB 1 m	1
6	Ḃ-field meter	BPM 02	1
7	Ė-field meter	EPM 02	1
8	Case		1
9	Quick guide		1
10	User manual		1

The scope of delivery may deviate depending on the respective order.

RF power field coupling 1 GHz