APPLICATION NOTE

I•CODE

Coil Design Guide

Product Specification
September 2002

Revision 3.0

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1 CONTENTS

2 INTRODUCTION

2.1 Scope

This application note should give a guidance for designing the coil for I•CODE Label IC’s.

2.2 Structure of the Document

This Document is subdivided in three Parts.

The first part handles the theory that is used for the label design and includes the general behaviour of the I•CODE IC.

The Second part handles the suggested measurement methods that are used while the design process.

The third part is a suggested design flow that can be used to design specific inlet/label/card coils. This part includes the practical used formulas and matrix suggestions and the decision parameters to determine the correct and best suitable design.

2.3 Flow for Inlet Industrialisation

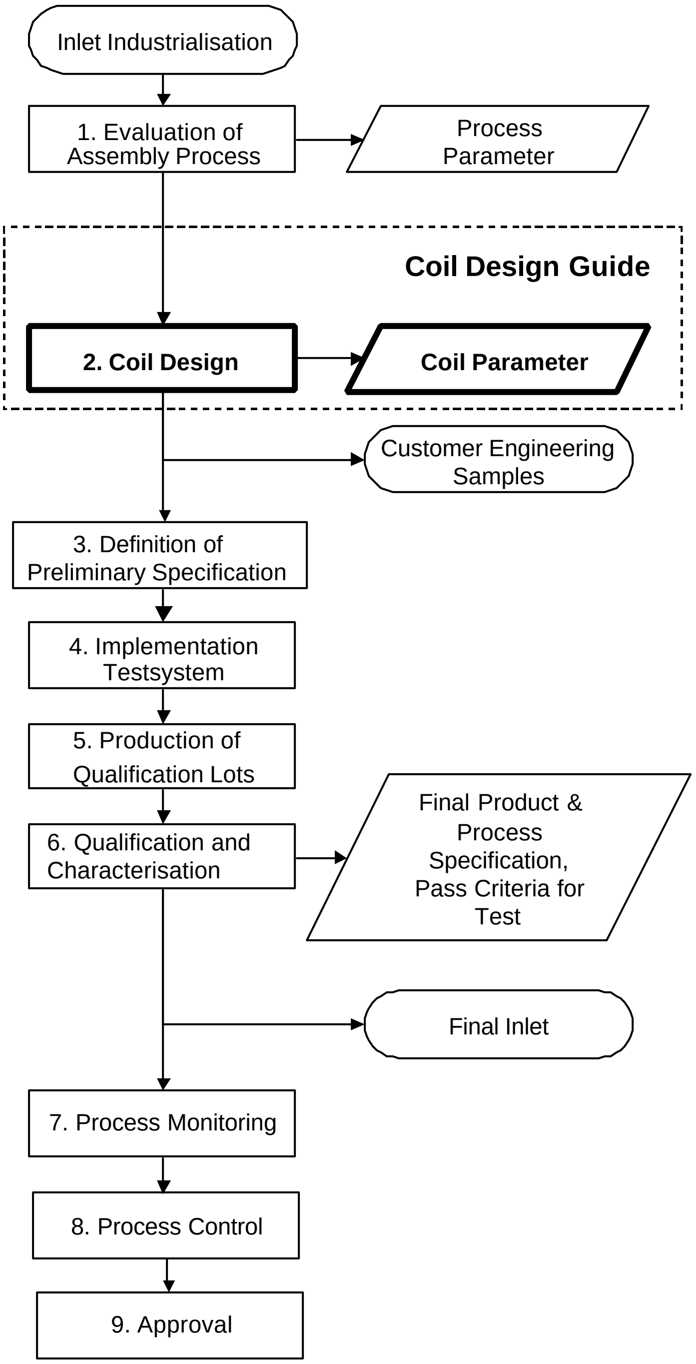


Fig. 1: Flow for inlet industrialisation

The coil design is part of the I•CODE Inlet industrialisation flow. Other steps like qualification and test are described in the application note " I•CODE Inlet Industrialisation".

2.4 Abbreviations

A_c	Average coil area
a_{avg} , b_{avg}	Average dimensions of the coil
a_{max}, b_{max}	Maximum dimensions of the coil
a_o, b_o	Overall dimensions of the coil
C_c	Coil capacitance
C_{br}	Bridge capacitance
C_{Con}	Capacitance due to the connection I•CODE Label IC – coil
C_{IC}	I•CODE Label IC input capacitance
C_{IC0}	I•CODE Label IC input capacitance for unloaded condition
C_{ICT}	I•CODE Label IC input capacitance for threshold condition
C_{in}	Designed inlet capacitance
C_{it}	Inter turn capacitance of the coil
C_{pl}	Parallel equivalent capacitance of the label
C_{pl0}	Parallel equivalent capacitance of the label for unloaded condition
C_{plT}	Parallel equivalent capacitance of the label for threshold condition
f	Frequency
f_{op}	Operating frequency
f_R	Resonance frequency of the label
f_{R0}	Unloaded resonance frequency of the label
f_{RT}	Threshold resonance frequency of the label
f_{RTNom}	Threshold resonance frequency of the label considering a nominal C_{ICT}
f_{Ideal}	Ideal resonance frequency of the inlet
g	Gap between tracks
H_T	Threshold field strength
H_{Tmin}	Minimal threshold field strength
H_{Top}	Threshold field strength at operating frequency
I_1	Reader antenna current
L_{calc}	Inductance calculated out of geometrical coil parameters
L_o	Objective inductance of the coil
L_{pc}	Parallel equivalent inductance of the coil
L_{sc}	Series equivalent inductance of the coil
M	Mutual inductance between label antenna and reader antenna
N_c	Number of turns of the coil
p	Turn exponent
Q	Quality factor of the label
Q_0	Unloaded quality factor of the label
Q_{pc}	Quality factor of the coil for parallel equivalent circuit
Q_{sc}	Quality factor of the coil for series equivalent circuit
Q_T	Threshold quality factor of the label
R_{Con}	Resistance of the connection I•CODE Label IC – coil
R_{IC}	I•CODE Label IC input resistance
R_{IC0}	I•CODE Label IC input resistance for unloaded condition
R_{ICT}	I•CODE Label IC input resistance for threshold condition
R_{pc}	Parallel equivalent resistance of the coil
R_{pl}	Parallel equivalent resistance of the label
R_{pl0}	Parallel equivalent resistance of the label for unloaded condition
R_{plT}	Parallel equivalent resistance of the label for threshold condition
R_{sc}	Series equivalent resistance of the coil
t	Track thickness
$V_{LA\text{-}LB}$	I•CODE Label IC input voltage
$V_{LA\text{-}LB\ min}$	Minimal supply voltage for I•CODE Label IC operation

w	Track width

3 THEORY

3.1 The I•CODE Label IC

The I•CODE Label IC has to be connected to the coil with the pads LA and LB:

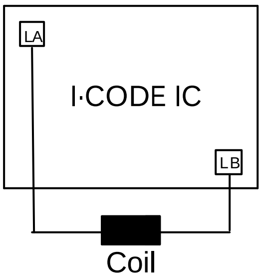


Fig. 2: I•CODE Label IC

3.1.1 EQUIVALENT CIRCUIT OF THE I•CODE LABEL IC

The following simple equivalent circuit describes the properties of the I•CODE Label IC which are relevant for the coil design.

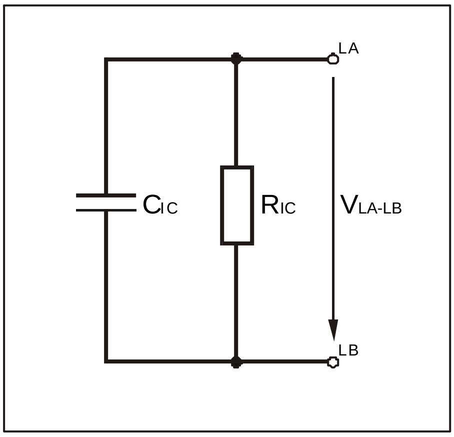


Fig. 3: Equivalent circuit of the I•CODE Label IC

R_{IC}	I•CODE Label IC input resistance
C_{IC}	I•CODE Label IC input capacitance

3.1.2 I•CODE LABEL IC INPUT RESISTANCE R_{IC}

The following diagram shows the typical behaviour of the input resistance over applied voltage V_{LA-LB} at operating frequency f_{op} = 13.56 MHz.

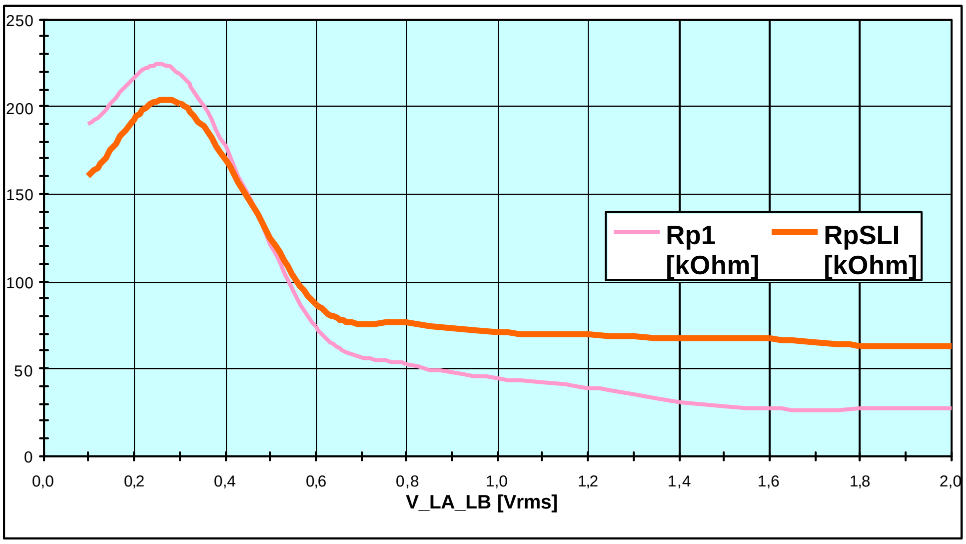


Fig. 4: R_{IC} vs. V_{LA-LB}

3.1.3 I•CODE LABEL IC INPUT CAPACITANCE C_{IC}

This electrical parameter of the I•CODE Label IC is the most important factor for the coil design.

The input capacitance depends on the applied chip voltage. The following diagram shows the typical behaviour of the input capacitance over applied voltage V_{LA-LB} at operating frequency f_{op} = 13.56 MHz.

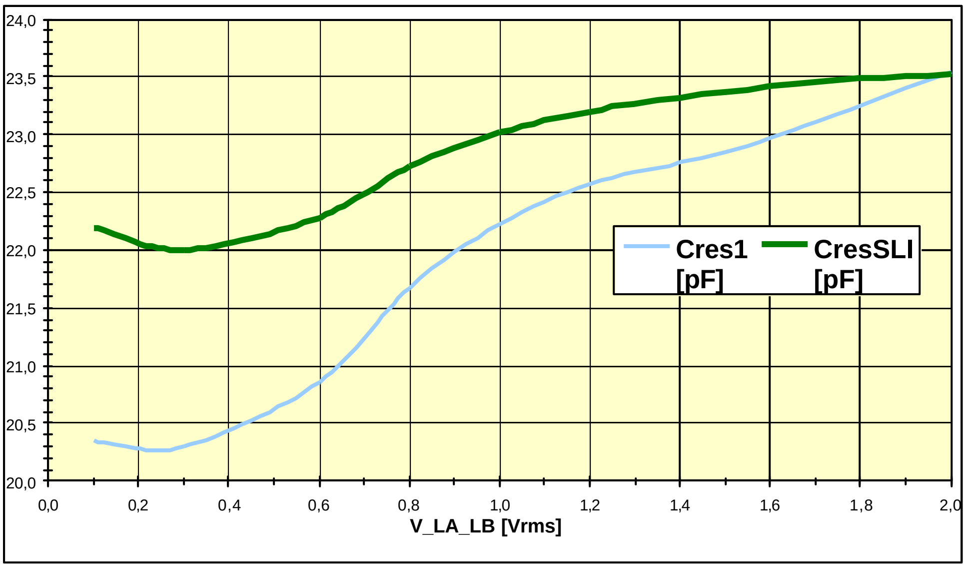


Fig. 5: C_{IC} vs. V_{LA-LB}

Remark: As it can be seen by Figures 5 the input characteristics of I•CODE1 and I•CODE SLI are slightly different, but - in the working point (threshold) - there is no difference in the C_{IC} value (23,5pF).

The following value of this capacitance for the given type of I•CODE Label IC is specified:

Type	C_{IC}	Measurement Conditions[1]
SL1 ICS30 01	23.5 pF ± 1.2 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
SL1 ICS31 01	97 pF ± 5 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
SL1 MOA2 S30	23.7 pF ± 1.2 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz
SL2 ICS20 01	23.5 pF ± 1.2 pF	V_{LA-LB} = 2 V_{rms}, f = 13.56 MHz

[1] Measured with HP 4285A LCR Meter

3.2 Equivalent Circuits

3.2.1 SERIES EQUIVALENT CIRCUIT OF THE COIL

The coil can be described by an inductance L_{sc} in series to a loss resistance R_{sc}. The coil capacitance C_c is in parallel to this series circuit. This capacitance consists of the inter-turn capacitance and a possibly designed inlet capacitance. The design of such an inlet capacitance is not considered in this application note.

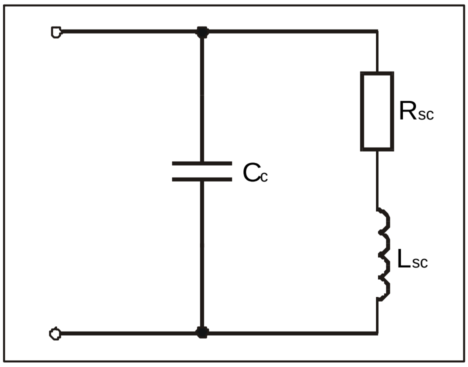


Fig. 6: Series equivalent circuit of the coil

R_{sc}	Series equivalent resistance of the coil
L_{sc}	Series equivalent inductance of the coil
C_c	Coil capacitance

The coil quality factor is calculated by

$$Q_{sc} = \frac{2 \cdot p \cdot f_{op} \cdot L_{sc}}{R_{sc}}$$

with operating frequency f_{op} = 13.56 MHz. If the quality factor is too low, the resistive part of the coil will consume too much power and therefore reduce the transmission range.

3.2.2 PARALLEL EQUIVALENT CIRCUIT OF THE COIL

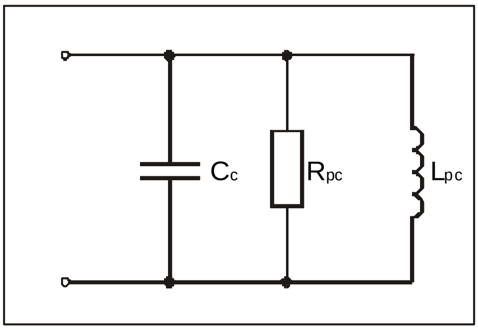


Fig. 7: Parallel equivalent circuit of the coil

R_{pc}	Parallel equivalent resistance of the coil
L_{pc}	Parallel equivalent inductance of the coil

The following applies:

$$L_{pc} = \frac{R_{sc}{}^{2} + \left(2 \cdot p \cdot f_{op} \cdot L_{sc}\right)^{2}}{\left(2 \cdot p \cdot f_{op}\right)^{2} \cdot L_{sc}} = L_{sc} \cdot \frac{1 + Q_{sc}{}^{2}}{Q_{sc}{}^{2}}$$

$$R_{pc} = \frac{R_{sc}{}^{2} + \left(2 \cdot p \cdot f_{op} \cdot L_{sc}\right)^{2}}{R_{sc}} = R_{sc} \cdot \left(1 + Q_{sc}{}^{2}\right)$$

$$Q_{pc} = \frac{R_{pc}}{2 \cdot p \cdot f_{op} \cdot L_{pc}} = Q_{sc}$$

3.2.3 EQUIVALENT CIRCUIT OF THE LABEL

The following figure shows the equivalent circuit of the whole label.

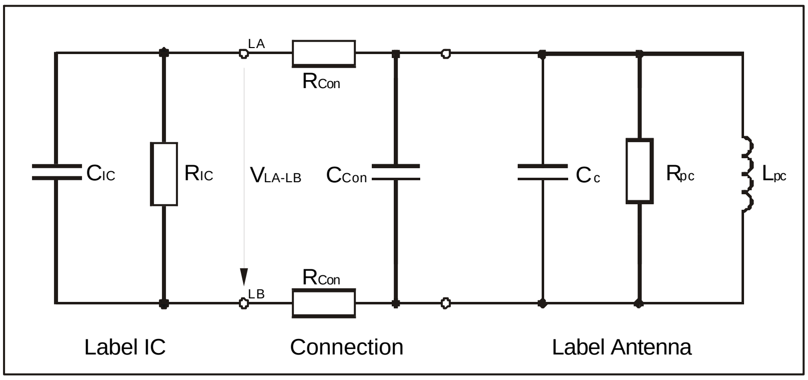


Fig. 8: Equivalent circuit of the label

R_{Con}	Resistance of the connection I•CODE Label IC – coil
C_{Con}	Connection capacitance

The I•CODE Label IC capacitance C_{IC} together with the coil capacitance and the parasitic connection capacitance forms a resonance circuit with the inductance of the coil.

The I•CODE Label IC input resistance R_{IC} together with the loss resistance of the coil and the connection resistance defines the quality factor of the label. This quality factor has an effect on the threshold field strength of the label and will be explained in the following sections.

R_{Con} should be kept as low as possible in order not to influence the total parallel equivalent resistance of the label R_{pl}. A relatively high connection resistance will decrease the total quality factor of the label and therefore decrease the transmission range.

C_{Con} describes the increase of the total label capacitance due to dielectric changes (under filler, adhesive, ..) in the connection area when the chip is applied to the coil.

Remark: The IC sizes has also an influence on the connection capacity C_{Con}. Therefore different values must be taken into account for the coil design for I•CODE1 and I•CODE SLI.

For $R_{Con} << 1\ \Omega$ the following simplified equivalent circuit can be used for the label:

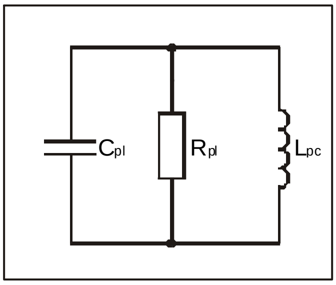


Fig. 9: Simplified equivalent circuit of the label

With:

$C_{pl} = C_{IC} + C_{Con} + C_c$ Parallel equivalent capacitance of the label

$R_{pl} = \frac{R_{IC} \cdot R_{pc}}{R_{IC} + R_{pc}}$ Parallel equivalent resistance of the label

3.3 Resonance Frequency and Quality Factor of the Label

Based on the simplified equivalent circuit the resonance frequency f_R of the label can be calculated with:

$$f_R = \frac{1}{2 \cdot p \cdot \sqrt{L_{pc} \cdot C_{pl}}}$$

f_R Resonance frequency of the label

The value of the I•CODE Label IC input capacitance C_{IC} depends on the chip input voltage V_{LA-LB} as shown in Fig. 5. Therefore the resonance frequency of the label changes with the IC input voltage.

Based on the simplified equivalent circuit (Fig. 9) the quality factor Q of the label at the measurement frequency can be calculated with:

$$Q = \frac{R_{pl}}{2 \cdot p \cdot f_{op} \cdot L_{pc}}$$

Q Quality factor of the label

The value of the I•CODE Label IC input resistance R_{IC} depends on the chip input voltage V_{LA-LB} as shown in Fig. 4. Therefore also the quality factor of the label changes with the IC input voltage.

3.3.1 UNLOADED RESONANCE FREQUENCY F_{R0} AND UNLOADED QUALITY FACTOR Q_0

The unloaded resonance frequency f_{R0} is the resulting resonance frequency for an IC input voltage below the IC rectifier threshold level.

Condition: $V_{LA-LB} < 0.3\ V_{rms}$

$$C_{pl0} = C_{IC0} + C_{Con} + C_c$$

C_{IC0}	I•CODE Label IC input capacitance for unloaded condition
C_{pl0}	Parallel equivalent capacitance of the label for unloaded condition

C_{IC0} represents the I•CODE Label IC input capacitance for an applied chip voltage below the threshold level of the rectifier diodes and corresponds to the typical value shown in Fig. 5.

$$f_{R0} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{pl0}}}$$

f_{R0}	Unloaded resonance frequency

The unloaded resonance frequency f_{R0} can be easily measured (see chapter 'Measurement Methods') and is therefore often used for a rough label characterization.

$$R_{pl0} = \frac{R_{IC0} \cdot R_{pc}}{R_{IC0} + R_{pc}}$$

R_{IC0}	I•CODE Label IC input resistance for unloaded condition
R_{pl0}	Parallel equivalent resistance of the label for unloaded condition

$$Q_0 = \frac{R_{pl0}}{2 \cdot \pi \cdot f_{op} \cdot L_{pc}}$$

Q_0	Unloaded quality factor

The unloaded quality factor Q_0 describes mainly the losses of the coil and the losses of the connection, because the input resistance of the I•CODE Label IC for this condition of the IC input voltage is very high (typically $R_{IC0} > 150$ kΩ, see Fig. 4).

3.3.2 THRESHOLD RESONANCE FREQUENCY F_{RT} AND THRESHOLD QUALITY FACTOR Q_T

The threshold resonance frequency f_{RT} is the resulting resonance frequency for the minimum operating input voltage of the IC.

Condition: $V_{LA\text{-}LB} = V_{LA\text{-}LB\,min}$

$V_{LA\text{-}LB\,min}$	Minimal supply voltage for I•CODE Label IC operation according to IC specification

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$

C_{ICT}	I•CODE Label IC input capacitance for threshold condition
C_{plT}	Parallel equivalent capacitance of the label for threshold condition

C_{ICT} represents the I•CODE Label IC input capacitance for minimal operating conditions and corresponds to the specified typical value measured with 2 V_{rms} (see Fig. 5).

$$f_{RT} = \frac{1}{2 \cdot \pi \cdot \sqrt{L_{pc} \cdot C_{plT}}}$$

f_{RT}	Threshold resonance frequency

$$R_{plT} = \frac{R_{ICT} \cdot R_{pc}}{R_{ICT} + R_{pc}}$$

R_{ICT}	I•CODE Label IC input resistance for threshold condition
R_{plT}	Parallel equivalent resistance of the label for threshold condition

R_{ICT} represents the I•CODE Label IC input resistance for the minimal operating conditions and corresponds to the shown typical value at 2 V_{rms} (see Fig. 4).

$$Q_T = \frac{R_{plT}}{2 \cdot p \cdot f_{op} \cdot L_{pc}}$$

Q_T Threshold quality factor

3.3.3 RESONANCE FREQUENCY SHIFT BETWEEN F_{R0} AND F_{RT}

The aim of the coil design procedure is to achieve a threshold resonance frequency f_{RT} = fop = 13.56 MHz. The shift between the threshold resonance frequency f_{RT} and the unloaded resonance frequency f_{R0} depends on the ratio of the coil inductance to the coil capacitance L_{pc}/C_c as the following calculation examples show.

Assumption: (see also Fig. 5)

C_{ICT} = 23.5 pF, $C_{IC0} \approx$ 20 pF, C_{Con} = 1 pF, f_{RT} = 13.56 MHz

Example 1: C_c = 2.0 pF

C_{plT} = 26.5 pF, f_{RT} = 13.56 MHz, -> L_{pc} = 5.2 µH

C_{pl0} = 23 pF, -> **f_{R0} = 14.55 MHz**

Example 2: C_c = 5.0 pF

C_{plT} = 29.5 pF, f_{RT} = 13.56 MHz, -> L_{pc} = 4.67 µH

C_{pl0} = 26 pF, -> **f_{R0} = 14.44 MHz**

Therefore each type of label (coil size, coil manufacturing technology, assembly process parameter) has its own optimum value for the unloaded resonance frequency f_{R0}.

Because of the different Input Capacitor characteristics at low voltages ($V_{LA-LB} < V_{LB-Lbmin}$ – Please refer to Chapter 3.1.3) the shift between f_0 and f_{RT} is also different between an I•CODE 1 and an I•CODE SLI label.

3.4 Threshold field strength H_T

This section gives formulas to calculate the threshold field strength H_T which is significant for the transmission range. The influence of the threshold resonance frequency f_{RT} and coil quality factor Q_{pc} on this field strength is figured out.

The voltage on the IC generated by the magnetic field of the reader with antenna current I_1 is given by:

$$V_{LA-LB} = \frac{2 \cdot p \cdot f \cdot M}{\left(\left(1 - \left(\frac{f}{f_R} \right)^2 \right)^2 + \left(\frac{2 \cdot p \cdot f \cdot L_{pc}}{R_{pl}} \right)^2 \right)^{\frac{1}{2}}} \cdot I_1$$

M	Mutual inductance between label antenna and reader antenna
I_1	Reader antenna current
f	Frequency

With the assumption that the turns of the label coil are concentrated on the average coil dimensions, the threshold field strength for I•CODE Label IC operation can be calculated with:

$$H_T = \frac{\left(\left(1 - \left(\frac{f}{f_{RT}} \right)^2 \right)^2 + \left(\frac{2 \cdot p \cdot f \cdot L_{pc}}{R_{plT}} \right)^2 \right)^{\frac{1}{2}}}{2 \cdot p \cdot f \cdot m_0 \cdot N_c \cdot A_c} \cdot V_{LA-LB\,\mathrm{min}}$$

N_c	Number of turns of the label coil
A_c	Average coil area calculated with average coil dimensions
$V_{LA\text{-}LB\ min}$	Minimal supply voltage for I•CODE Label IC operation

The following figure shows the behaviour of the threshold field strength H_T versus the frequency f of the inducing magnetic field for a label with the threshold resonance frequency f_{RT}.

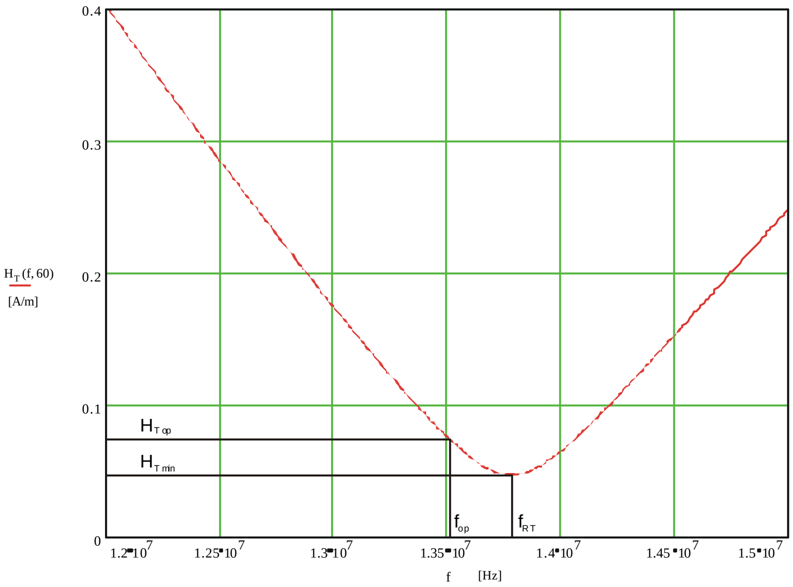


Fig. 10: Threshold field strength vs. frequency

The curve of the threshold field strength reaches its minimum at the threshold resonance frequency f_{RT} of the label. For f = f_{RT} the minimal threshold field strength $H_{T\,min}$ results in:

$$H_{T\ \min} = \frac{L_{pc}}{m_0 \cdot N_c \cdot A_c \cdot R_{plT}} \cdot V_{LA-LB\ \min}$$

At the operating frequency f_{op} the threshold field strength results in:

$$H_{T\ op} = \frac{\left(\left(1-\left(\frac{f_{op}}{f_{RT}}\right)^2\right)^2 + \left(\frac{2 \cdot p \cdot f_{op} \cdot L_{pc}}{R_{plT}}\right)^2\right)^{\frac{1}{2}}}{2 \cdot p \cdot f_{op} \cdot m_0 \cdot N_c \cdot A_c} \cdot V_{LA-LB\ \min}$$

Optimal designed label: f_{RT} = f_{op} = 13.56 MHz resulting in H_T=H_{Tmin}

3.4.1 INFLUENCE OF THE COIL QUALITY FACTOR ON THE MINIMAL THRESHOLD FIELD STRENGTH H_{TMIN}

The following figure shows the influence of the coil quality factor Q_{pc} on the minimal threshold field strength $H_{T\,min}$ for a label with the optimal threshold resonance frequency of f_{RT} = 13.56 MHz.

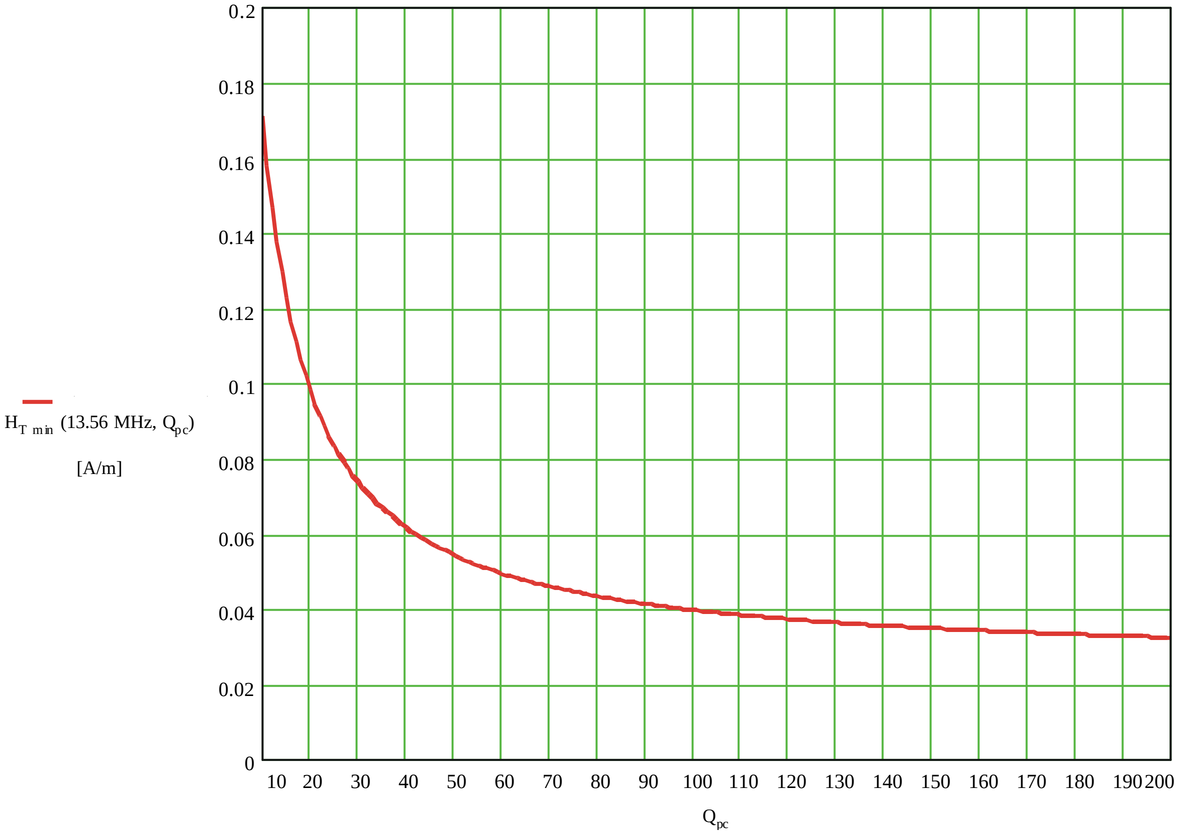


Fig. 11: Minimal threshold field strength vs. coil quality factor

A coil quality factor of $Q_{pc} < 60$ increases the minimal threshold field strength significantly.

4 MEASUREMENT METHODS

4.1 Coil Characterisation

The equivalent circuit of the coil can be determined by using the following measuring instruments with associated measuring principals.

4.1.1 IMPEDANCE ANALYZER WITH EQUIVALENT CIRCUIT CALCULATION

The following instruments among others can determine the series or parallel equivalent circuit by measuring the magnitude and the phase of the impedance of the connected coil.

Instruments: HP 4194A

HP 4294A

HP 4195A

HP 4295A

The coil must be connected to the analyzer by using an appropriate test fixture which do not influence the coil parameters (no metal parts near the coil, ..).

The analyzer must be calibrated (open, short and load compensation at the calibration plane) and the test fixture compensated (open, short compensation at the connection points) according to the manual before each measurement.

Settings: $|Z|, \Theta$

Center frequency: 13.56 MHz

Span: 2 MHz

Advantage:

- Fast and simple method

Disadvantages:

- Low accuracy of the measurement results especially of the loss resistance for high quality factor coils (Q_{pc} > 60).

4.1.2 RESONANCE METHOD

The following instruments are among others suitable for this measurement principal.

HP 4194A

HP 4294A

HP 4195A

HP 4295A

HP 4285A LCR Meter with suitable software or manual frequency sweep

Measurement Principle:

For this measurement principle two different capacitors have to be connected to the coil in order to form two different resonance circuits. The two resulting resonance frequencies have to be determined. The equivalent circuit parameters L_{pc} and C_c of the coil are calculated out of these frequencies. In addition, the bandwidth of one of these resonance circuits has to be measured to calculate the quality factor Q_{pc} of the label coil.

A measuring coil has to be connected to the instrument. A short-compensation has to be performed with this measuring coil connected to the terminals of the instrument.

The measuring coil has to meet the following requirements:

- About the same dimensions as the label coil
- 1 turn
- Low parasitic capacitance
- High quality factor

The measurement ($|Z|$, Θ) of the bare compensated measuring coil (no label coil near to it) shows a very low magnitude of the impedance ($|Z| < 50$ mΩ). The resonance circuit (coil with connected capacitor) has to be positioned in the near ambience of the measuring coil now (1 – 2 cm distance). The measurement ($|Z|$, Θ)of the measuring coil shows a well defined maximum of the impedance and a run of the phase Θ from the positive region to the negative region now. The resonance frequency is found at the zero crossing of the phase Θ which should be at the same frequency as the maximum of the impedance $|Z|$.

Resonance frequency: f_r @ $\Theta = 0°$

The bandwidth B of the resonance circuit is found by the difference of the frequency which shows a phase of $\Theta = -45°$ and the frequency which shows a phase of $\Theta = +45°$.

Bandwidth: B = $f_{-45°} - f_{+45°}$

Measurement Preparations:

- The measurement coil has to be connected to the test fixture of the instrument
- A short correction of the measurement coil has to be performed and switched on
- Settings: $|Z|, \Theta$, frequency sweep

Measurement Procedure:

- A precisely determined capacitor **C_{a1}** with high quality factor has to be connected to the coil terminals.
- Positioning of the resonance circuit in a defined distance to the measuring coil (1 – 2 cm distance).
- Measurement of first resonance frequency **f_{r1}** and the bandwidth **B**
- A second precisely determined capacitor **C_{a2}** with high quality factor has to be connected to the label antenna terminals.
- Measurement of second resonance frequency **f_{r2}** at the same distance.

The capacitance values of C_{a1} and C_{a2} should be chosen in that way to get resonance frequencies around 13.56 MHz. For example C_{a1}=22pF and C_{a2} = 27 pF for a 23.5 pF I•CODE Label IC coil design. The measurement of the bandwidth B has to be performed with the capacitance which is closer to the specified input capacitance of the I•CODE Label IC.

Calculation of the equivalent circuit parameters of the coil:

$$L_{pc} = \frac{1}{4 \cdot p^2 \cdot (C_{a1} - C_{a2})} \cdot \left(\frac{1}{f_{r1}^{\ 2}} - \frac{1}{f_{r2}^{\ 2}} \right)$$

$$C_c = \frac{C_{a1} \cdot f_{r1}^{\ 2} - C_{a2} \cdot f_{r2}^{\ 2}}{f_{r2}^{\ 2} - f_{r1}^{\ 2}}$$

$$Q_{pc} = \frac{f_{r1}}{B} = \frac{f_{r1}}{f_{-45} - f_{+45}}$$

$$R_{pc} = Q_{pc} \cdot 2 \cdot p \cdot f_{op} \cdot L_{pc}$$

Advantage:

- High accuracy
- LCR Meter sufficient for measurement (Less expensive instrument)

Disadvantages:

- Precise determination of the used capacitance (including all parasitics of the connection to the coil) values is necessary.

4.2 Label Characterisation

4.2.1 UNLOADED RESONANCE FREQUENCY F_{R0} AND UNLOADED QUALITY FACTOR Q_0

The following instruments are among others suitable for this measurement principal.

HP 4194A

HP 4294A

HP 4195A

HP 4295A

HP 4285A LCR Meter with suitable software or manual frequency sweep

The measurement procedure is the same as described in section 4.1.2. The I•CODE Label IC is connected to the coil terminals instead of a capacitor.

The measuring coil has to meet the same requirements and the same measurement preparations must be performed as listed under 4.1.2

The label has to be positioned in a defined distance (1 – 2 cm) to the measuring coil.

The magnitude and the phase of the impedance of the measuring coil with positioned label must be determined by the measuring instrument. A low current or voltage source level must be chosen for this measurement to keep the voltage on the I•CODE Label IC below the diode threshold level (see 3.3.1).

The unloaded resonance frequency f_{R0} of the label is that frequency where the phase of the impedance is zero. The unloaded quality factor Q_0 is calculated out of the measured bandwidth B_0.

$$Q_0 = \frac{f_{R0}}{B_0} = \frac{f_{R0}}{f_{-45} - f_{+45}}$$

4.2.2 THRESHOLD RESONANCE FREQUENCY F_{RT}

The following instruments are among others suitable for this measurement principal.

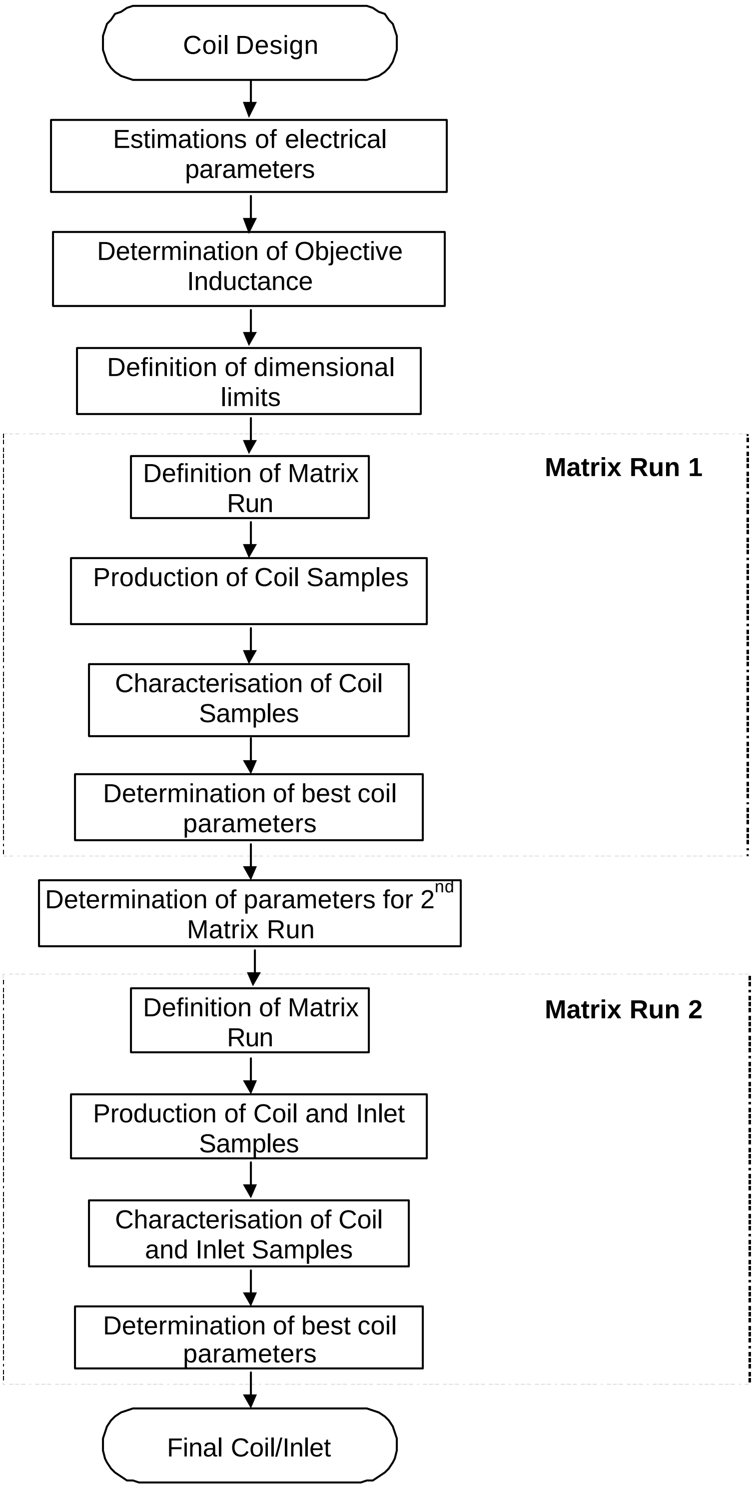
HP 4294A Impedance Analyzer

HP 4285A LCR Meter with suitable software or manual frequency sweep

The measurement principle is the same as for the measurement of the unloaded resonance frequency. The only difference is to choose a constant current source to produce a constant field strength. The measuring current must be adjusted to a level which generates the minimum operating input voltage for the I•CODE Label IC (compare section 3.3.2).

5 COIL DESIGN PROCEDURE

5.1 Design Flow



5.2 Ideal Threshold Frequency f_{Ideal} determination

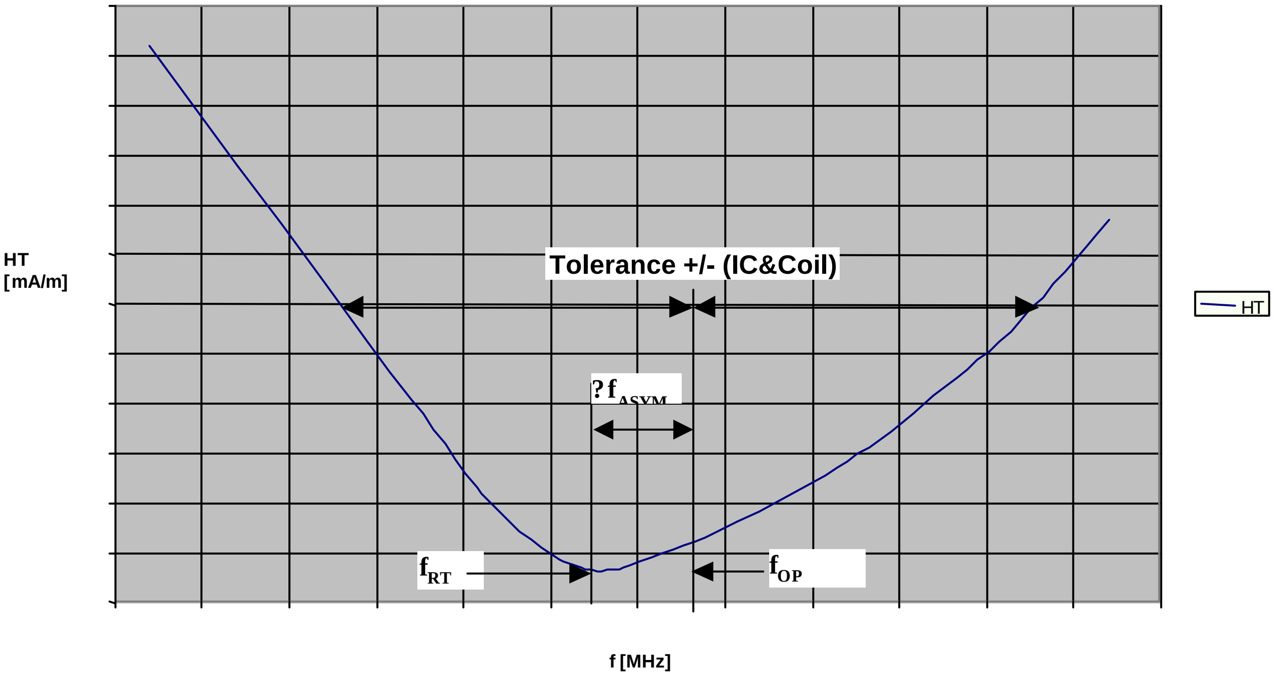
Based on the application it is necessary to determine what resonance frequency the inlet should be tuned to.

Usually the ideal threshold frequency f_{Ideal} is 13,56 MHz (refer to §3.4)

In real applications the ideal threshold resonance frequency f_{Ideal} could deviate from the theoretic value as described in the paragraphs §5.2.1 to §5.2.3.

5.2.1 CONSIDERING THE SHIFT DUE TO ASYMMETRIC H_T CURVE: ΔF_{ASYM}

A shift of approximately 100kHz could be considered



This picture shows the asymetry.

5.2.2 CONSIDERING THE INFLUENCE OF LAMINATION: ΔF_{LAM}

A shift of approximately 100-400kHz could be considered

(value depending on the lamination process, the used paper, the used adhesive....)

To find out the exact shift it is suggested to measure the shift with some samples.

5.2.3 CALCULATION OF THE IDEAL INLET RESONANCE FREQUENCY F_{IDEAL}

$$f_{Ideal} = f_{OP} - \Delta f_{ASYM} + \Delta f_{LAM}$$

5.3 Rectangular Coils

5.3.1 CALCULATION OF FIRST MATRIX RUN COILS

5.3.1.1 Estimation of the Coil Capacitance C_c

In order to be able to calculate roughly the objective inductance L_o of the coil, it is necessary to estimate the capacitance C_c of the coil. This capacitance can be split up into the always existent coil inter turn capacitance C_{it}, the additional capacitance due to a possibly realised bridge C_{br} and a possibly designed on inlet capacitance C_{in}.

The coil inter turn capacitance C_{it} is dependent upon the technology used for the coil manufacturing. The following table shows the estimated values for some often used technologies.

Coil manufacturing technology	C_{it} [pF]
Wired	5-7
Etched	2-4
Printed	2-4

The capacitance of a possibly realised bridge C_{br} depends on the bridge length and bridge width.

Estimated value: C_{br} = 1 – 5 pF

An additional capacitance realised on the inlet C_{in} depends on the capacitor area. This capacitance is difficult to estimate, so it is recommended to make a measurement of this on inlet capacitor.

$$C_c = C_{it} + C_{br} + C_{in}$$

5.3.1.2 Estimation of the Connection Capacitance C_{Con}

The connection capacitance can be estimated by choosing a value out of the following range:

C_{Con} = 0.5 – 2 pF

5.3.1.3 Calculation of Objective Coil Inductance L_o based on an estimated Label Capacitance C_{plT}

$C_{plT} = C_{ICT} + C_{Con} + C_c$ Estimated parallel equivalent capacitance of the label

With C_{ICT} = 23.5 pF

$$L_o = \frac{1}{(2 \cdot p \cdot f_{RT})^2 \cdot C_{plT}}$$

With $f_{RT} = f_{Ideal}$

5.3.1.4 Equations

The inductance of the coil out of geometrical parameters estimates to:

$$L_{calc} = \frac{m_0}{p} \cdot [x_1 + x_2 - x_3 + x_4] \cdot N_c{}^p$$

With:

$$d = \frac{2 \cdot (t + w)}{p}$$

$$a_{avg} = a_o - N_c \cdot (g + w)$$

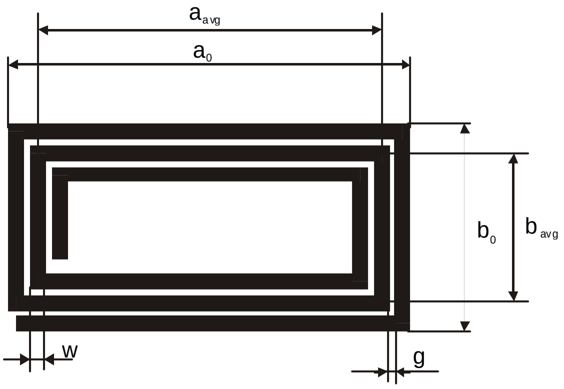
$$b_{avg} = b_o - N_c \cdot (g + w)$$

$$x_1 = a_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(a_{avg} + \sqrt{a_{avg}{}^2 + b_{avg}{}^2}\right)}\right]$$

$$x_2 = b_{avg} \cdot \ln\left[\frac{2 \cdot a_{avg} \cdot b_{avg}}{d \cdot \left(b_{avg} + \sqrt{a_{avg}{}^2 + b_{avg}{}^2}\right)}\right]$$

$$x_3 = 2 \cdot \left[a_{avg} + b_{avg} - \sqrt{{a_{avg}}^2 + {b_{avg}}^2} \right]$$

$$x_4 = \frac{a_{avg} + b_{avg}}{4}$$



Variables:

a_o, b_o	Overall dimensions of the coil
a_{avg}, b_{avg}	Average dimensions of the coil
t	Track thickness
w	Track width
g	Gap between tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent

5.3.1.5 Maximum coil dimensions a_{max}, b_{max}

The maximum dimensions of the coil a_{max} and b_{max} are determined by the application which the label is designed for.

Therefore the starting point for the calculations is always:

$$a_o = a_{max}$$

$$b_o = b_{max}$$

The actual overall dimensions of the coil a_o and b_o can also be smaller than a_{max} and b_{max} in some cases (big labels) but the product $A_c \cdot N_c$ should be kept always as high as possible (see ”Minimal threshold field strength”)!

$$A_c = a_{avg} \cdot b_{avg} \qquad \text{Average coil area}$$

5.3.1.6 Gap between tracks g

The minimal gap between the tracks g_{min} is defined by the coil production process.

To get the highest possible average coil area:

$$g = g_{min}$$

5.3.1.7 Track thickness t and track width w

For Aluminium and Copper coils a track thickness of $t \geq 30$ µm should give a sufficient quality factor ($Q_{pc} > 60$) even for a small track width w.

For printed coils the track thickness should be chosen as high as possible to get highest possible quality factors.

The track width w remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width w not to small as it influences the quality factor Q_{pc} and a variation of the track width w is needed for the second matrix run as well.

5.3.1.8 Estimation of Turn Exponent p

Under the assumption that all turns are concentrated on the outline of the coil, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100 %, the inductance is proportional to N_c^2.

As this is not possible to realise the following table gives estimated values for the turn exponent p for different coil manufacturing technologies.

Coil manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85
Printed	1.7 – 1.8

5.3.1.9 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o
p
a_{max}, b_{max}
t
g

The calculation of the inductance L_o is based on estimated values and also the calculation of the coil parameters at this time can only be made approximately. Therefore the inductance of the matrix run coils should be varied within ± 20 % of the estimated objective inductance L_o.

i ... First matrix run coil number

i	1	2	3	4	5
$L_{calc, i}$	0.8 L_o	0.9 L_o	L_o	1.1 L_o	1.2 L_o
$a_{o, i}$					
$b_{o,i}$					
$N_{c, i}$					
w_i					

The coil parameters $a_{o, i}$, $b_{o, i}$, $N_{c, i}$ and w_i must be iterative varied until $L_{calc, i}$ is equal to the given percentage of the estimated objective inductance L_o. During this coil parameter determination it must be always attempted to keep the product $A_{c, i} \cdot N_{c, i}$ as high as possible!

5.3.2 EQUIVALENT CIRCUIT MEASUREMENT AND EVALUATION OF FIRST MATRIX RUN COILS

The parallel equivalent circuit of the matrix run coils must be determined (see also chapter ”Measurement Methods”).

i	1	2	3	4	5
$C_{c, i}$					
$L_{pc, i}$					
$R_{pc,i}$					

$Q_{pc,\ i}$					

A coil quality factor of $Q_{pc,\ i} < 60$ increases the minimal threshold field strength significantly (see Fig. 11). In this case it is recommended to increase the track width or thickness and to start again with a new matrix run calculation.

5.3.2.1 Calculation of Objective Coil Inductance $L_{o,i}$

The value of the coil capacitance $C_{c,i}$ is determined for all coils now. These values are used to calculate the objective coil inductance $L_{o,i}$ for all coils again.

$$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,\ i}$$ Parallel equivalent capacitance of the label with coil i

$$L_{o,i} = \frac{1}{(2 \cdot p \cdot f_{RT})^2 \cdot C_{plT,i}}$$

With $f_{RT} = f_{Ideal}$

5.3.2.2 Minimal Difference between $L_{pc,i}$ and $L_{o,i}$

A coil of the matrix run must be determined where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The coil number i with minimum ΔL_i: j = i

j... Matrix run coil number with minimum ΔL_j

Parameter Summary:

j	
$L_{pc, j}$	
$C_{c, j}$	
$a_{o, j}$	
$b_{o,j}$	
$N_{c, j}$	
w_j	

The coil j is the basing point for the second matrix run calculations.

5.3.2.3 Determination of Turn Exponent p

For the chosen coil j the precise turn exponent p has to be calculated now.

$$a_o = a_{o,j}$$

$$b_o = b_{o,j}$$

$$L_{pc,j} = L_{calc} = \frac{m_0}{p} \cdot \left[x_1 + x_2 - x_3 + x_4\right] \cdot N_{c,j}{}^{p}$$

$$p = \frac{\ln\left(\dfrac{L_{pc,j} \cdot p}{m_0 \cdot \left[x_1 + x_2 - x_3 + x_4\right]}\right)}{\ln N_{c,j}}$$

5.4 Circular Coils

Generally a lot of the next points are equal to §6.1. To give a better overview the paragraphes were separated completely.

5.4.1 CALCULATION OF FIRST MATRIX RUN COILS

5.4.1.1 Estimation of the Coil Capacitance C_c

In order to be able to calculate roughly the objective inductance L_o of the coil, it is necessary to estimate the capacitance C_c of the coil. This capacitance can be split up into the always existent coil inter turn capacitance C_{it}, the additional capacitance due to a possibly realised bridge C_{br} and a possibly designed on inlet capacitance C_{in}.

The coil inter turn capacitance C_{it} is dependent upon the technology used for the coil manufacturing. The following table shows the estimated values for some often used technologies.

Coil manufacturing technology	C_{it} [pF]
Wired	5-7
Etched	2-4
Printed	2-4

The capacitance of a possibly realised bridge C_{br} depends on the bridge length and bridge width.

Estimated value: C_{br} = 1 – 5 pF

An additional capacitance realised on the inlet C_{in} depends on the capacitor area. This capacitance is difficult to estimate, so it is recommended to make a measurement of this on inlet capacitor.

$$C_c = C_{it} + C_{br} + C_{in}$$

5.4.1.2 Estimation of the Connection Capacitance C_{Con}

The connection capacitance can be estimated by choosing a value out of the following range:

C_{Con} = 0.5 – 2 pF

5.4.1.3 Calculation of Objective Coil Inductance L_o based on an estimated Label Capacitance C_{plT}

$$C_{plT} = C_{ICT} + C_{Con} + C_c$$

Estimated parallel equivalent capacitance of the label

With C_{ICT} = 23.5 pF

$$L_o = \frac{1}{\left(2 \cdot \mathbf{p} \cdot f_{RT}\right)^2 \cdot C_{plT}}$$

With $f_{RT} = f_{Ideal}$

5.4.1.4 Equations

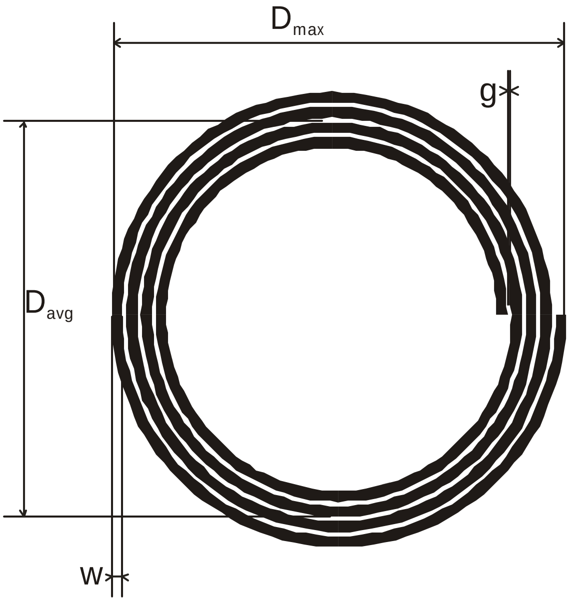
The inductance of the coil out of geometrical parameters estimates to:

$$L_{calc}\left[nH\right] = 2 \cdot l \cdot \left[\ln \frac{l}{d} - 1{,}07\right] \cdot N^{p}$$

$$l = D_{avg} \cdot \mathbf{p}$$

$$D_{avg} = D_o - N \cdot \left(g + w\right)$$

$$d = \frac{2 \cdot \left(w + t\right)}{p}$$



Variables:

D_{max}	Coil diameter [cm]
D_o	Coil diameter [cm]
t	Track thickness
w	Track width
g	Gap between tracks
N_c	Number of turns
d	Equivalent diameter of the track
p	Turn exponent
D_{avg}	Average coil Diameter[cm]
l	average coil circumference [cm]

5.4.1.5 Maximum coil dimensions D_{max}

The maximum dimension of the coil D_{max} is determined by the application which the label is designed for.

Therefore the starting point for the calculations is always:

$$D_o = D_{max}$$

The actual overall dimension of the coil D_o can also be smaller than D_{max} in some cases (big labels) but the product $A_c \cdot N_c$ should be kept always as high as possible (see ”Minimal threshold field strength”)!

$$A_c = D_{avg}{}^2 \cdot \frac{\pi}{4} \qquad \text{Average coil area}$$

5.4.1.6 Gap between tracks g

The minimal gap between the tracks g_{min} is defined by the coil production process.

To get the highest possible average coil area:

$$g = g_{min}$$

5.4.1.7 Track thickness t and track width w

For Aluminium and Copper coils a track thickness of t ≥ 30 µm should give a sufficient quality factor ($Q_{pc} > 60$) even for a small track width w.

For printed coils the track thickness should be chosen as high as possible to get highest possible quality factors.

The track width w remains as fit-parameter for the calculation of the inductance L_{calc}. It is recommended to choose the track width w not to small as it influences the quality factor Q_{pc} and a variation of the track width w is needed for the second matrix run as well.

5.4.1.8 Estimation of Turn Exponent p

Under the assumption that all turns are concentrated on the outline of the coil, so all magnetic flux passes the enclosed area of all turns (no stray field) and the magnetic coupling between the turns is 100 %, the inductance is proportional to N_c^2.

As this is not possible to realise the following table gives estimated values for the turn exponent p for different coil manufacturing technologies.

Coil manufacturing technology	p
Wired	1.8 – 1.9
Etched	1.75 – 1.85

Printed	1.7 – 1.8

5.4.1.9 Matrix run definition

The following values have to be fixed before starting the matrix run calculations:

L_o
p
D_{max}
t
g

The calculation of the inductance L_o is based on estimated values and also the calculation of the coil parameters at this time can only be made approximately. Therefore the inductance of the matrix run coils should be varied within ± 20 % of the estimated objective inductance L_o.

i ... First matrix run coil number

i	1	2	3	4	5
$L_{calc, i}$	0.8 L_o	0.9 L_o	L_o	1.1 L_o	1.2 L_o
$D_{o, i}$					
$N_{c, i}$					
w_i					

The coil parameters $D_{o,i}$, $N_{c,i}$ and w_i must be iterative varied until $L_{calc, i}$ is equal to the given percentage of the estimated objective inductance L_o. During this coil parameter determination it must be always attempted to keep the product $A_{c, i} \cdot N_{c ,i}$ as high as possible!

5.4.2 EQUIVALENT CIRCUIT MEASUREMENT AND EVALUATION OF FIRST MATRIX RUN COILS

The parallel equivalent circuit of the matrix run coils must be determined (see also chapter ”Measurement Methods”).

i	1	2	3	4	5
$C_{c, i}$					
$L_{pc, i}$					
$R_{pc,i}$					
$Q_{pc, i}$					

A coil quality factor of $Q_{pc,\ i}$ < 60 increases the minimal threshold field strength significantly (see Fig. 11). In this case it is recommended to increase the track width or thickness and to start again with a new matrix run calculation.

5.4.2.1 Calculation of Objective Coil Inductance $L_{o,i}$

The value of the coil capacitance $C_{c,i}$ is determined for all coils now. These values are used to calculate the objective coil inductance $L_{o,i}$ for all coils again.

$C_{plT,i} = C_{ICT} + C_{Con} + C_{c,\,i}$ Parallel equivalent capacitance of the label with coil i

$$L_{o,i} = \frac{1}{(2 \cdot \pi \cdot f_{RT})^2 \cdot C_{plT,i}}$$

With $f_{RT} = f_{Ideal}$

5.4.2.2 Minimal Difference between $L_{pc,i}$ and $L_{o,i}$

A coil of the matrix run must be determined where the difference of measured inductance $L_{pc,i}$ and objective inductance $L_{o,i}$ is a minimum.

$$\Delta L_i = \left| L_{pc,i} - L_{o,i} \right|$$

i	1	2	3	4	5
$L_{pc,i}$					
$L_{o,i}$					
ΔL_i					

The coil number i with minimum ΔL_i: j = i

j... Matrix run coil number with minimum ΔL_j

Parameter Summary:

j	
$L_{pc, j}$	
$C_{c, j}$	
$D_{o, j}$	
$N_{c, j}$	
w_j	

The coil j is the basing point for the second matrix run calculations.

5.4.2.3 Determination of Turn Exponent p

For the chosen coil j the precise turn exponent p has to be calculated now.

$$D_o = D_{o,j}$$

$$p = \frac{\ln\left(\dfrac{L_{pc,j}}{2 \cdot l_j \cdot \left\{\ln \cdot \left({l_j}/{d_j} \right) \cdot 1{,}07 \right\}}\right)}{\ln N_{c,j}}$$

5.5 Calculation of Second Matrix Run Coils

5.5.1 RECTANGULAR COILS

$$a_o = a_{o,j}$$

$$b_o = b_{o,j}$$

$$L_{calc} = \frac{m_0}{p} \cdot \left[x_1 + x_2 - x_3 + x_4 \right] \cdot N_{c,j}{}^{p}$$

5.5.2 CIRCULAR COILS

$$D_o = D_{o,j}$$

$$L_{calc}\left[nH\right] = 2 \cdot l \cdot \left[\ln \frac{l_j}{d_j} - 1{,}07 \right] \cdot N_{c,j}{}^{p}$$

5.5.3 TABEL FOR SECOND MARTIX RUN COILS

The calculation of the inductance $L_{o,j}$ is still based on an estimated connection capacitance C_{Con} and also the coil parameters have influence on each other giving a non linear system. Therefore the inductance of the second matrix run coils should be varied within ± 8 % of the objective inductance $L_{o,j}$.

k… Second matrix run coil number

k	1	2	3	4	5
$L_{calc,k}$	0.92 $L_{o,j}$	0.96 $L_{o,j}$	$L_{o,j}$	1.04 $L_{o,j}$	1.08 $L_{o,j}$
w_k					

Only the coil parameter track width w_k (a_{avg}, b_{avg} resp. D_{avg}) should be varied until $L_{calc,\,k}$ is equal the given percentage of the objective inductance $L_{o,j}$. In order to keep the accuracy of the calculation on a high level the overall dimensions a_o, b_o, D_o and the gap between the tracks g as well as the track thickness t should not be varied anymore.

5.6 I•CODE Label IC Assembly on Second Matrix Run Coils

The IC's used for finding the optimal coil design should be taken out of the centre of one wafer. The input capacitance of this IC's is very close to the average input capacitance value of the wafer. This average input capacitance value of the used wafer can be found on the map disk of the specific wafer in the CRES-file.

Alternatively it also is possible to ask this information from Philips (mailto: info.bli@philips.com). **Please specify Wafer Batch Number and Wafer Number.**

The difference between specified nominal value and average value of the used wafer should be taken into account when choosing the optimal coil.

5.7 Measurements

5.7.1 COIL (WITHOUT IC)

The inductance $L_{p,k}$ has to be measured.

Result Table

k	1	2	3	4	5
$L_{p,k}$					

5.7.2 INLET (WITH IC)

The unloaded resonance frequency $f_{R0,k}$, the unloaded quality factor $Q_{0,k}$ and the threshold resonance frequency $f_{RT,k}$ of the second matrix run labels should be characterised (see 4.2 Label Characterisation).

A label must be determined where the value of the measured threshold resonance frequency $f_{RT,k}$ is closest to the optimal value. The used track width w_k of this label defines the optimum track width for the coil.

Result Table

k	1	2	3	4	5
$f_{rt,k}$					
$f_{R0,k}$					
$Q_{0,k}$					

The values $f_{R0,k}$ and $Q_{0,k}$ are only measured to verify that the quality of the coil is sufficient (please refer to chapter 3.3.1) and to know the unloaded resonance frequency f_0 as a reference value for this label.

5.8 Decision on the best coil parameters

To decide on the best parameters of the coil, the Nominal IC capacitance C_{ICTNom} has to be considered.

5.8.1 CONSIDERING THE NOMINAL IC CAPACITANCE $C_{ICT\ NOM}$

First you have to calculate the parallel Capacitance of the Label $C_{plT,k}$ ($C_{plT,k}$ includes $C_{con,k}$ and $C_{C,k}$)

$$C_{plT,k} = \frac{1}{L_{pc,k} \cdot (2 \cdot p \cdot f_{RT,k})^2}$$

The value of C_{ICT} of the IC's from the wafers you used can be asked at Philips with wafer batch number and wafer number.

Because of the difference between the C_{ICT} of your used IC and the nominal C_{ICTNom} you have a shift between the measured $f_{RT,k}$ and the nominal $f_{RT\ Nom,k}$ of this label.

$$f_{RTNom,k} = f_{RT,k} \cdot \frac{\sqrt{C_{plT,k}}}{\sqrt{C_{plT,k} - C_{ICT} + C_{ICTNom}}}$$

k	1	2	3	4	5
$C_{plT,k}$					
$f_{RTNom,k}$					

Theoretically the ideal f_{RTNom} of a Label is $f_{OP..}$ Due to the influence of lamination and the unsymmetrical behaviour of H_T we are considering shifts in real life. This leads to the Ideal resonance frequency fIdeal as described in chapter §5.2

5.8.2 CHOOSING THE BEST COIL

Calculate the difference between the nominal resonance frequency f_{RTNom} and the ideal resonance frequency f_{Ideal}

$$\Delta f_{Ideal-RTNom,k} = \left| f_{Ideal} - f_{RTNom,k} \right|$$

k	1	2	3	4	5
$f_{Ideal-RTNom,k}$					

The optimum coil is the coil that’s nearest to fIdeal.

$$\Delta f_{Ideal-RTNom,k} = Minimum$$

Summary Tabel of Parameters of Coil k:

k	
$L_{pc,\,k}$	
$C_{c,\,k}$	
$a_{o,\,k}$	
$b_{o,k}$	
$N_{c,\,k}$	
w_k	

6 REVISION HISTORY

REVISION	DATE	CPCN	PAGE	DESCRIPTION
2.0	July 1997	-		revised version
2.1	May 2002	-		Improved description of coil design procedure
3.0	August 2002	-		Add circular coil formulas; Ideal Coil selection, add I•CODE SLI
		-		
		-		
		-		
		-		
		-		

Table 6-1: Document Revision History

7 DEFINITIONS

Data sheet status	
Objective specification	This data sheet contains target or goal specifications for product development.
Preliminary specification	This data sheet contains preliminary data; supplementary data may be published later.
Product specification	This data sheet contains final product specifications.
Limiting values	
Limiting values given are in accordance with the Absolute Maximum Rating System (IEC 134). Stress above one or more of the limiting values may cause permanent damage to the device. These are stress ratings only and operation of the device at these or at any other conditions above those given in the Characteristics section of the specification is not implied. Exposure to limiting values for extended periods may affect device reliability.	
Application information	
Where application information is given, it is advisory and does not form part of the specification.	

8 LIFE SUPPORT APPLICATIONS

These products are not designed for use in life support appliances, devices, or systems where malfunction of these products can reasonably be expected to result in personal injury. Philips customers using or selling these products for use in such applications do so on their own risk and agree to fully indemnify Philips for any damages resulting from such improper use or sale.

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