磁性器件的模拟和设计:

GeckoMAGNETICS

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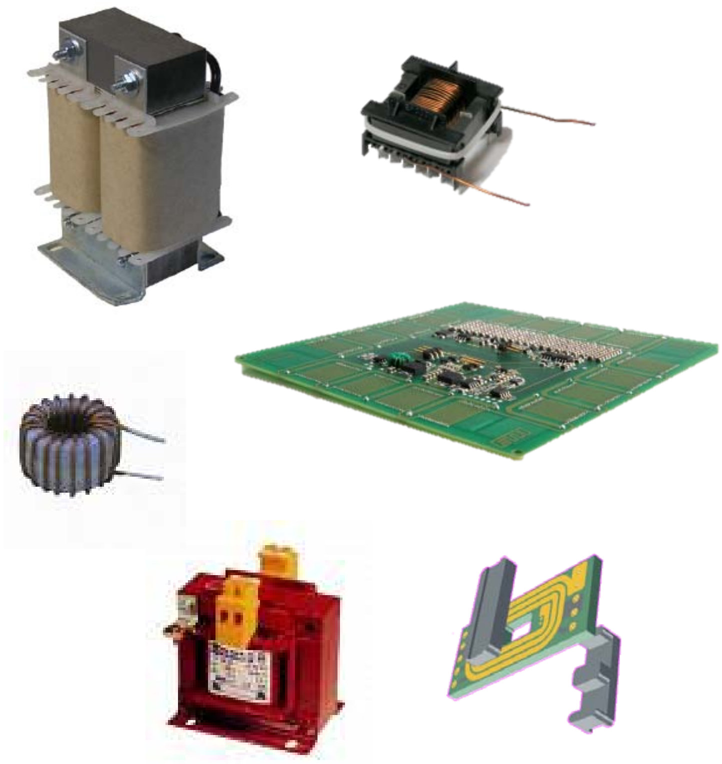
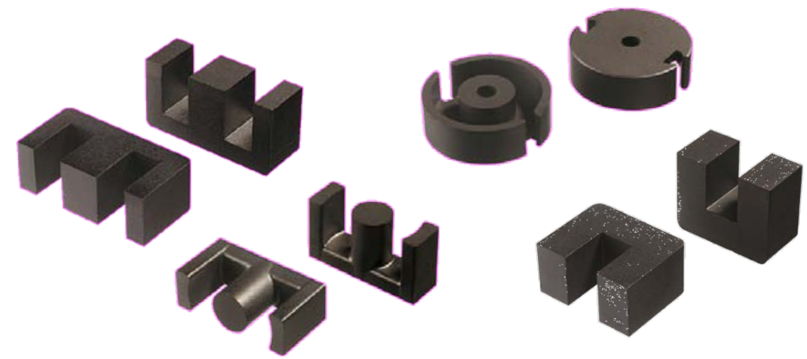
引言
功率磁性器件 – 宽广的选项范围

电感/ 变压器



www.wagnergrimm.ch, www.ferroxcube.com

磁芯形状



www.ferroxcube.com

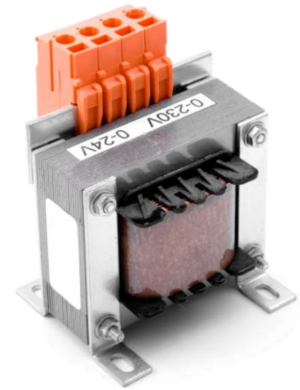
导体形状

www.pack-feindraehte.de, www.jiricek.de

Gecko-Simulations AG, 苏黎世, 瑞士

A Spin-Off Company from ETH Zürich

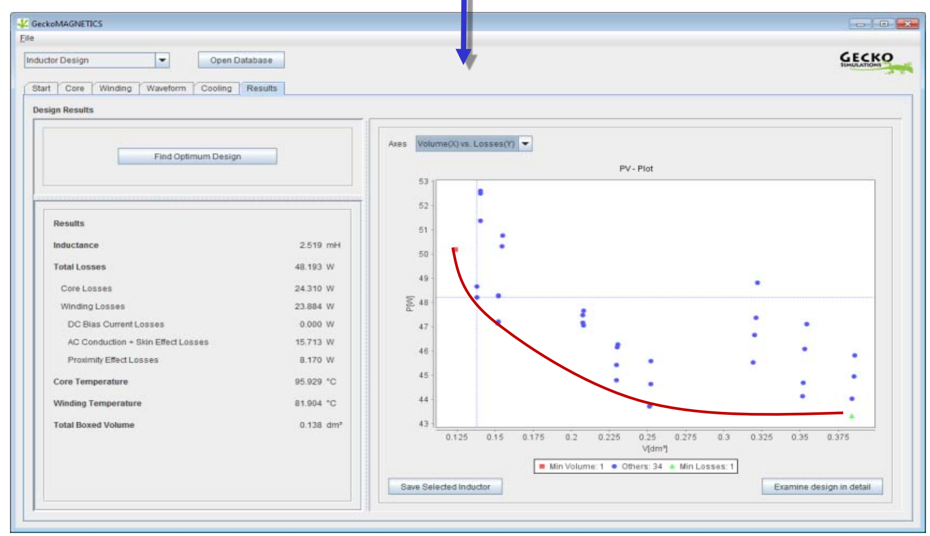
GeckoMAGNETICS –
轻松准确模拟设计磁芯器件



绕组损耗
- 实心线
- 利兹线
- 铜箔，邻近效应
- 扁宽，邻近效应

磁芯损耗
- 直流叠加
- 温度因素
- 不同激励波形

散热模型
- 自然对流
- 通风强制冷却



GeckoMAGNETICS – 绕组损耗模型

绕组损耗的计算和优化是乏味任务，但很直接。

先决条件:
    给定的电流波形

磁场分布已经知道或者可以导出:
- 依赖方位
- 频率

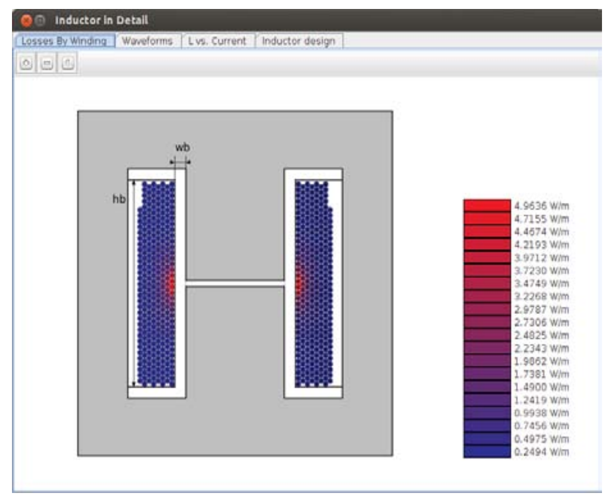
材料参数(导线状态, 温度.)

绕组几何尺寸和位置（实心，利兹, 铜箔…)

→ 所有模型参数都熟知，容易得到

绕组损耗的物理解析属线性!

→ 傅里叶变换是合理假设前提



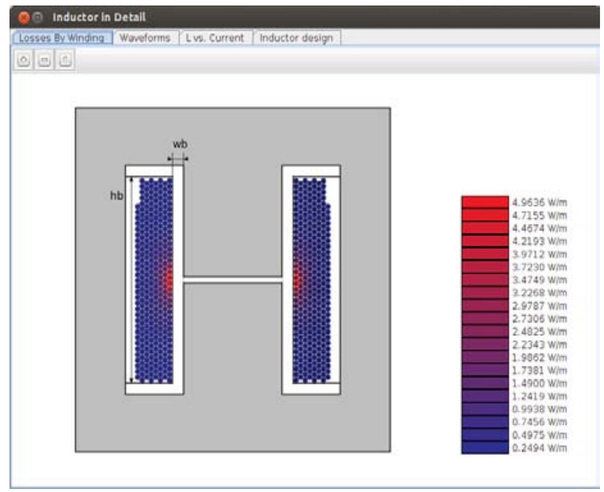
GeckoMAGNETICS －绕组损耗模型

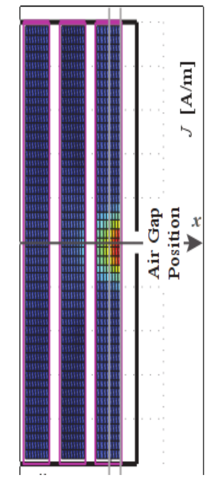
绕组损耗计算:

- 两位唱计算足够了
- 气隙的合并由众多虚拟的绕组气隙组成
- 磁芯边界：“镜像方法”
- 实心铜线解析方案已有

-利兹还有可选项

- 铜箔和扁平铜线：场模拟需要确定电流的分布情况!





肌肤效应(实心线) [1]

$$P_S = \frac{4}{\sigma \pi d^2} \frac{\xi}{2} \frac{\hat{I}^2}{2} \cdot \frac{K_{Ber}(0,\xi) K'_{Bei}(0,\xi) - K_{Bei}(0,\xi) K'_{Ber}(1,\xi)}{K'_{Ber}(0,\xi)^2 + K'_{Bei}(0,\xi)^2}$$

邻近效应(实心线) [1]

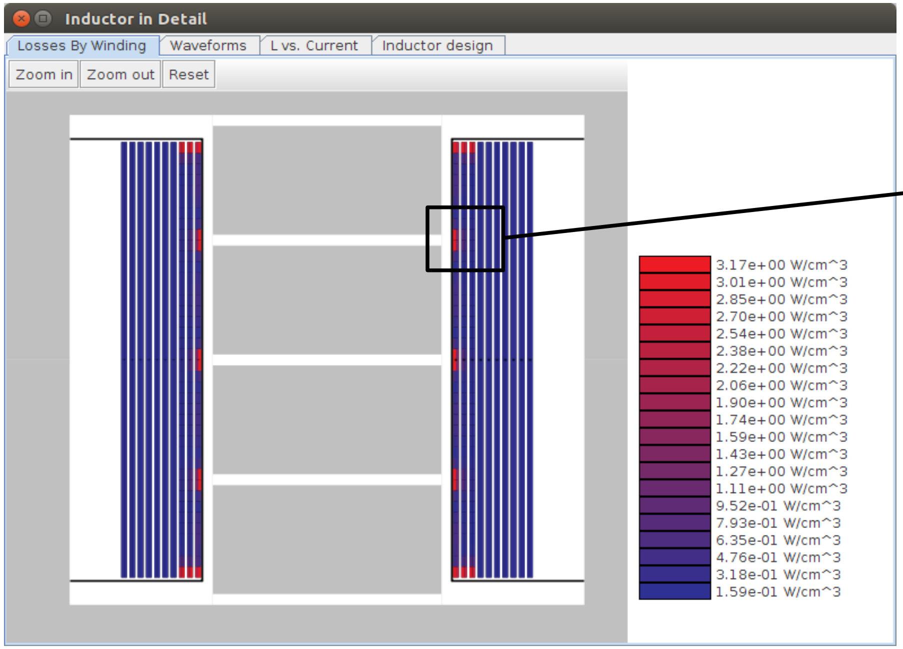
$$P_P = \frac{2\pi\xi}{\sigma} \hat{H}^2 \cdot \frac{K_{Ber}(2,\xi) K'_{Bei}(0,\xi) + K_{Bei}(2,\xi) K'_{Ber}(0,\xi)}{K_{Ber}(0,\xi)^2 + K_{Bei}(0,\xi)^2}$$

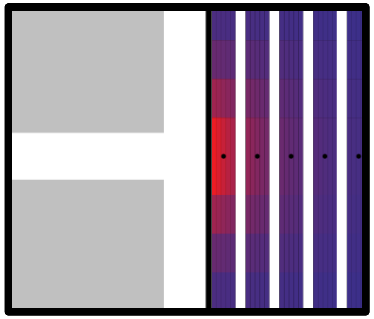
[1] J.A. Ferreira, “Analytical computation of AC resistance of round and rectangular litz wire windings ,“ IEE Proceedings B, Vol. 139, No. 1, January, 1992, Page(s): 21-25.

GECKO SIMULATIONS

GeckoMAGNETICS – 非常准确模拟绕组损耗

例子，铜箔绕组损耗





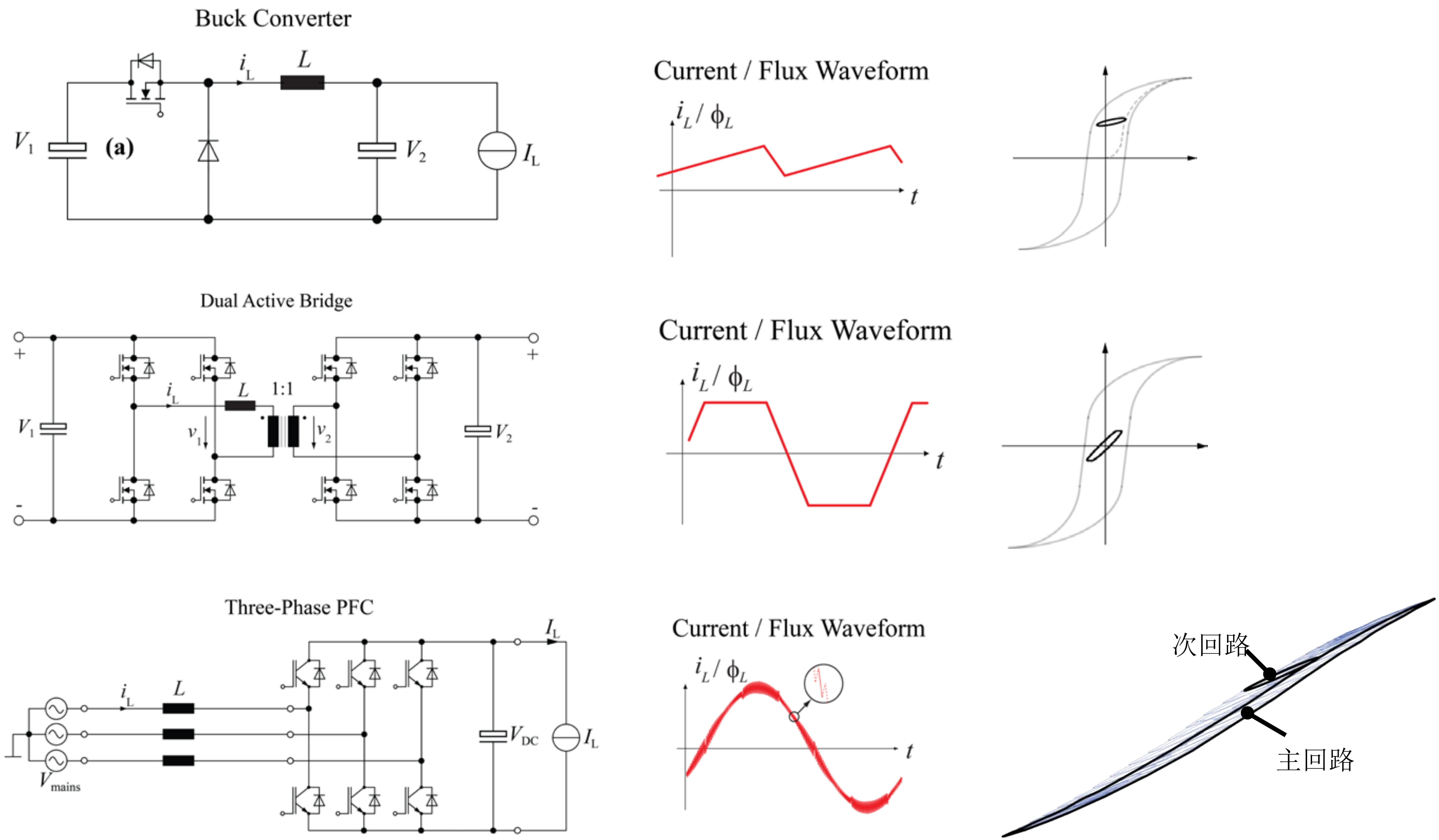
铜箔绕组计算需要电磁场的场求解，因为电流发布未知.

→ **快速电磁场的场求解根据部分等效元件电路方法 [2] 被包含在GeckoMAGNETICS 内用以准确计算2D 铜箔绕组损耗.**

[2] A. Müsing, J. W. Kolar, et Al., “Fast Method for the Calculation of Power Losses in Foil Windings”, Proc. of 17th ECCE Europe 2015, Geneva, Switzerland, Sept. 8-10, 2015.

GeckoMAGNETICS – 磁芯损耗模型

电力电子磁器件的典型电流/磁场强度激励波形

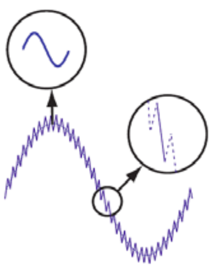


GeckoMAGNETICS －磁芯损耗模型

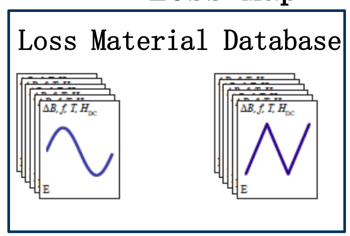
磁芯损耗的物理原理还完全被理解!

- 极其非线性
- 没有物理模型 → 仅仅经验损耗公式 (如 Steinmetz)
- GeckoMAGNETICS: 磁阻，数据库和改善Steinmetz模型的结合

“The best of both worlds” (Steinmetz & Loss Map approach)



Loss Map



$$k, k_i, \alpha, \beta, \alpha_r, \beta_r, q_r, \tau$$

$$P_v = \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\, dt + \sum_{l=1}^{n} Q_{rl} P_{rl} \longrightarrow \frac{P}{V}$$

GeckoMAGNETICS - Loss Map Core Loss Modeling

改善Steinmetz公式可用于功耗密度针对于不同激励波形的计算[3] ：

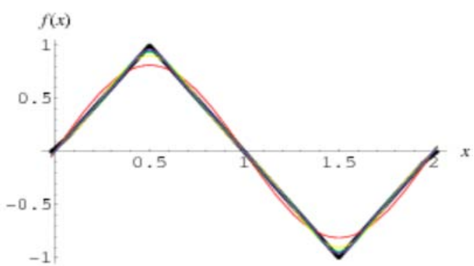
$$P_{\mathrm{v}} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^{\alpha} (\Delta B)^{\beta-\alpha}\,\mathrm{d}t$$

$$k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi} |\cos\theta|^{\alpha} 2^{\beta-\alpha}\,\mathrm{d}\theta}$$

→ 换算方波和正弦波测量数据

- 公式运行相当好!

- 举例: 三角波用原来Steinmetz公式
  (假设功耗线性) 铁氧体, f = 200 kHz, D=0.5, ΔB = small



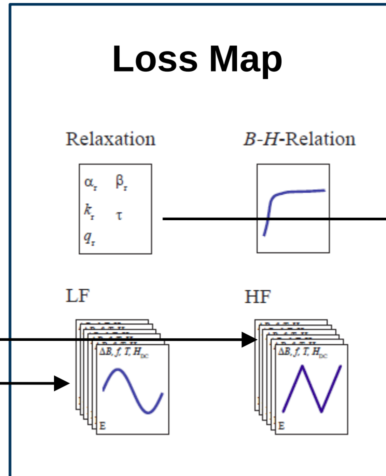
Fourier Series + Steinmetz

$$f(x) = \frac{8}{\pi^2}\sum_{n=1,3,5,\ldots}^{\infty} \frac{(-1)^{(n-1)/2}}{n^2}\sin\left(\frac{n\pi x}{L}\right)$$

→ 30 % difference in P_v results compared to iGSE

[3] C. R. Sullivan, “Improved calculation of core loss with nonsinusoidal waveforms,” in Ind. Appl. Conf. 2001. 36th IEEE IAS Annual Meeting, vol. 4, pp. 2203 - 2210, 2001

GeckoMAGNETICS －磁芯损耗模型

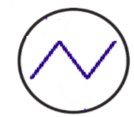


(I)

(II)

Evaluated for the according piecewise-linear flux segment

$$P_\mathrm{v} = \frac{1}{T}\int_0^T k_i \left|\frac{\mathrm{d}B}{\mathrm{d}t}\right|^\alpha (\Delta B)^{\beta-\alpha}\,\mathrm{d}t$$



$$\frac{P}{V}$$

Three loss map operating points are required in order to extract the parameters α, β, and k or k_i.

$$P_{\mathrm{v}1} = k_i\left(2f_1\right)^\alpha\left(\Delta B_1\right)^\beta$$

$$P_{\mathrm{v}2} = k_i\left(2f_2\right)^\alpha\left(\Delta B_2\right)^\beta$$

$$P_{\mathrm{v}3} = k_i\left(2f_3\right)^\alpha\left(\Delta B_3\right)^\beta$$

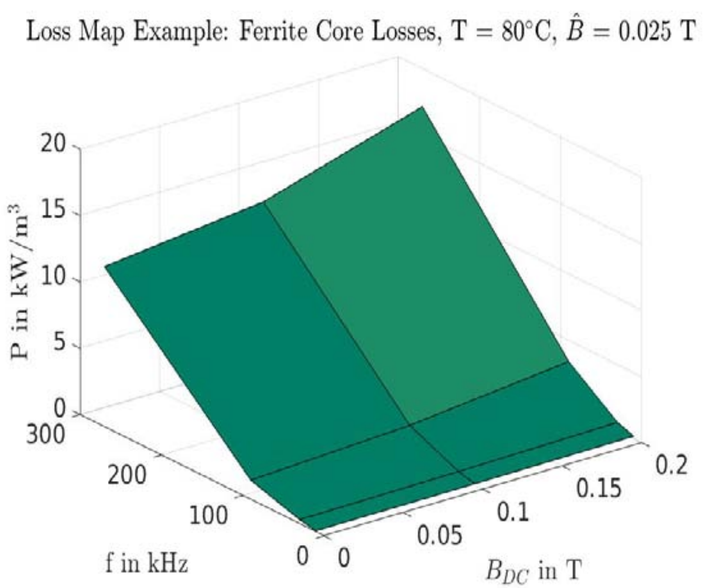
These equations arise when one evaluates the iGSE for symmetric triangular waveforms.

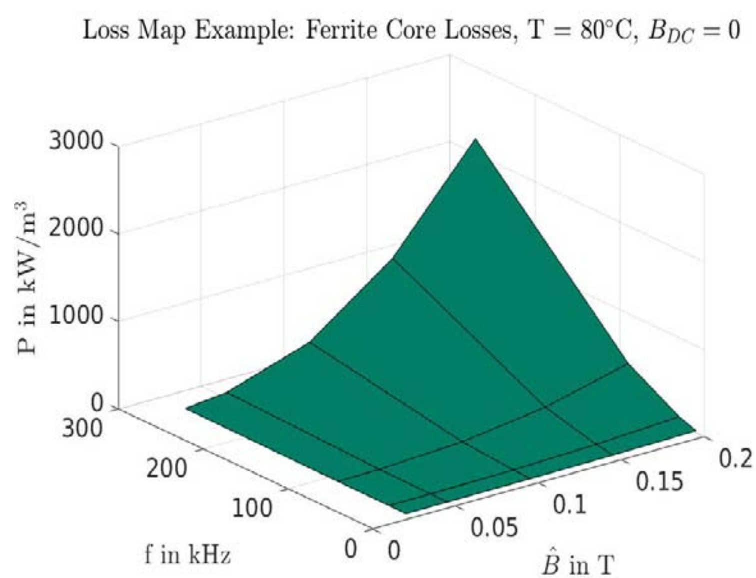
[4] J. Mühlethaler, J. W. Kolar, et Al., “Core Losses Under the DC Bias Condition Based on Steinmetz Parameters” IEEE Trans. on Power Electr., Vol. 27, No. 2, Feb. 2012.

GeckoMAGNETICS －磁芯损耗模型

磁芯损耗计算误差，忽略直流叠加效应(iGSE)
和材料非线性，举例：

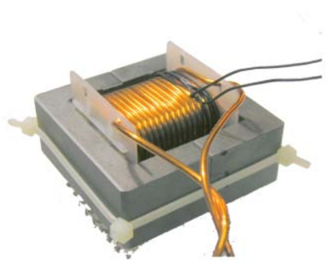
- Buck converter, I_{avg} = 10A, ΔI = 0.4 A, D = 0.7, f = 200 kHz
- 铁氧体E磁芯设计的电感 有3段发布气隙
- 磁芯损耗结果兼顾直流叠加效应: 200 mW. 忽略H_{DC}: P = 90 mW
- 占空比D: D = 0.5: 180 mW... D = 0.9: 231 mW

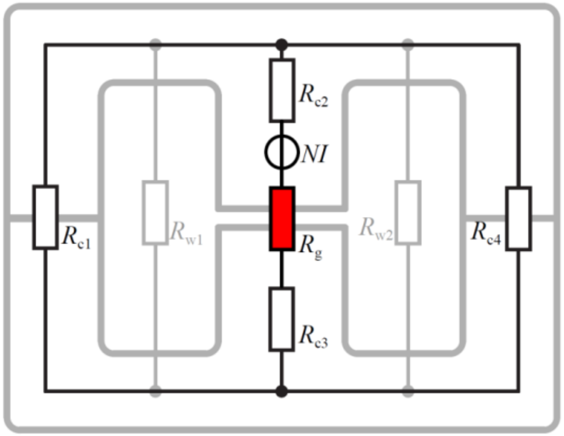




磁通密度基于磁阻的计算

- 磁芯损耗计算(iGSE) 是根据磁通密度 B(t)
- B(t) 场计算如果按照有限元方法进行计算无法满足快速模拟的需求
- 磁阻解析法计算结果类似于有限元计算方法
- 气隙在磁阻计算是要特别注意





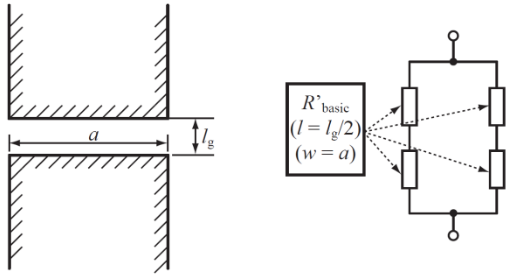
A reluctance model is needed in order to:

计算电感值 ($L = N^2/R_{tot}$)
计算饱和电流
计算杂散磁场
计算磁通密度

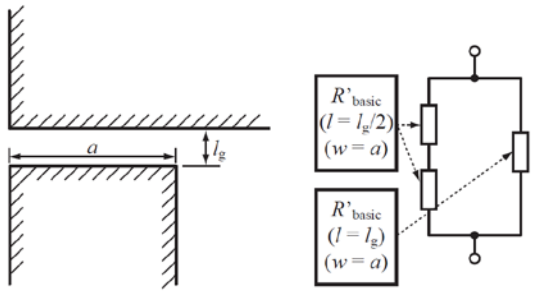
准确损耗计算模型!

气隙磁阻计算

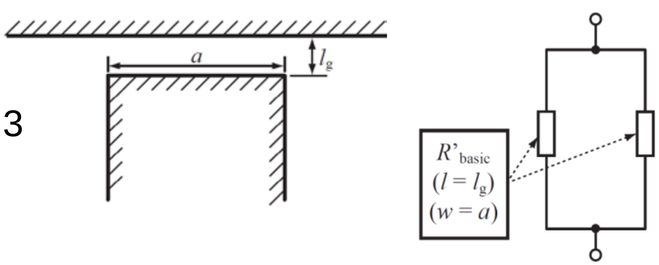
Air Gap Type 1



Air Gap Type 2

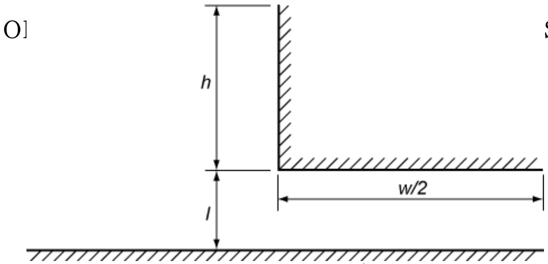


Air Gap Type 3



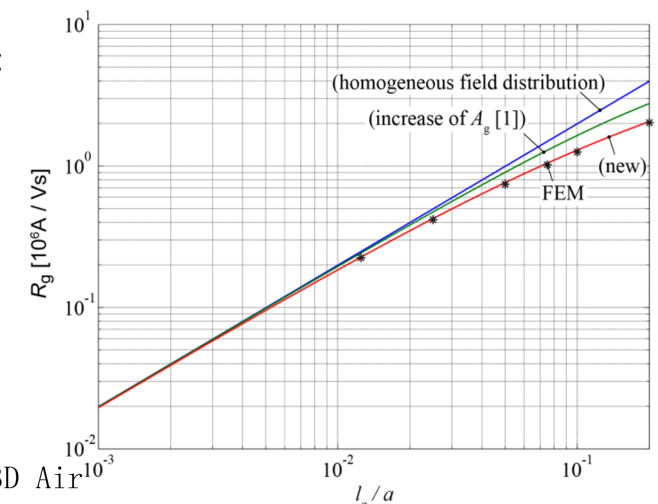
Basic Structure [5] for the Air Gap Calculation

Based o sforms



$$R'_{basic} = \frac{1}{\mu_0 \left[\frac{w}{2l} + \frac{2}{\pi} \left(1 + \ln \frac{\pi h}{4l} \right) \right]}$$

Results:



[5] J. Mühlethaler, J. W. Kolar, A. Ecklebe, “A Novel Approach for 3D Air Gap Reluctance Calculations”, 8th ECCE Asia, Korea, May 30-June 3, 2011.

材料非线性，展示饱和特性

非线性效应通常不直观，用数学模型计算非常困难。

从线路解 (如 GeckoCIRCUITS):
得到电流，电压波形:

nonlinear „secant " inductance: $$L_s(i) = \frac{N \cdot \Phi}{i} = \frac{\Psi}{i}$$

small signal: $$L_d(i) = \frac{\mathrm{d}(N \cdot \Phi)}{\mathrm{d}i} = \frac{\mathrm{d}\Psi}{\mathrm{d}i}$$

$$v(t) = L_d(i) \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{\mathrm{d}\Psi}{\mathrm{d}i} \cdot \frac{\mathrm{d}i}{\mathrm{d}t} = \frac{\mathrm{d}\Psi}{\mathrm{d}t} =$$
$$\frac{\mathrm{d}\left[i \cdot L_s(i)\right]}{\mathrm{d}t} = L_s(i) \cdot \frac{\mathrm{d}i}{\mathrm{d}t} + i \cdot \frac{\mathrm{d}L_s(i)}{\mathrm{d}t}$$

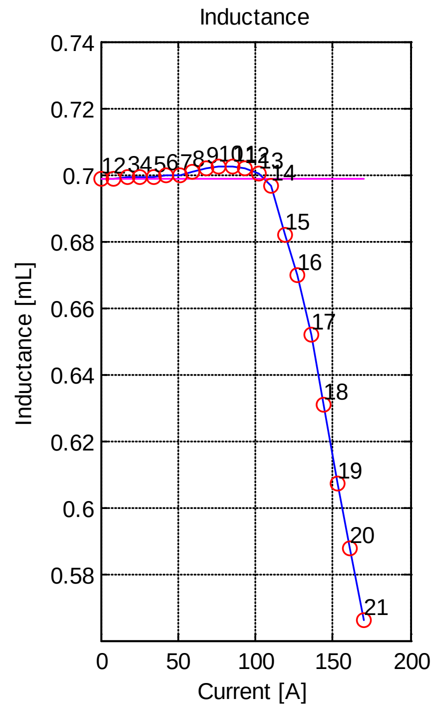
$$\rightarrow L_s(i) = \frac{1}{i} \int_0^i L_s(i')\, di'$$

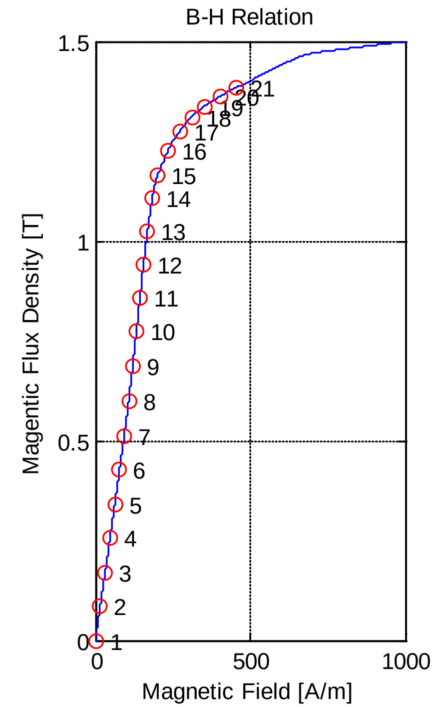
Energy equivalent nonlinear inductance:

$$L_e(i) = \frac{2}{i^2} \int_0^i i \cdot L_s(i')\, di'$$

„磁阻世界“:
非线性电感值的计算

$$L = \frac{N^2}{R_{\mathrm{tot}}(I)}$$





GeckoMAGNETICS – 功能完备的环境

这里仅仅**提及功率磁器件基**础**知**识(**磁芯**损**耗**,绕组损**耗**) **而在工程**设计**中我**们还**要注意以下** ：

- 变压器，主要和杂散电感值的计算
- 股价尺寸，绕组排布
- 共模和差模电感
- 线路解配合使用Co-Simulation (GeckoCIRCUITS)
- 散热模型
- 热反馈(磁芯尺寸的非线性，Newton iterations)
- 优化和脚本 (e.g. Matlab 角本界面)

GeckoMAGNETICS
设计流程 － 设计电感

设计电感

↓

1） 设定 L*， T_{max}

↓

2） 选择不同尺寸
选择不同材料

↓

3） 选择不同绕组

↓

4） 选择波形

↓

5） 选择冷却方案

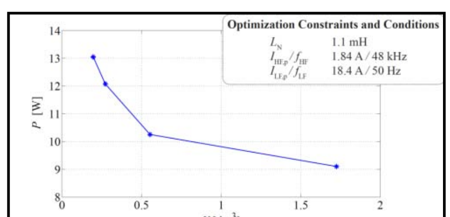
↓

6） 计算

user selects:
1. Several Core Geometries
(either several pre-defined cores OR
user sets the ranges of core geometry parameters for
one Core Type)
2. Several Core Materials

→ n_1 磁芯

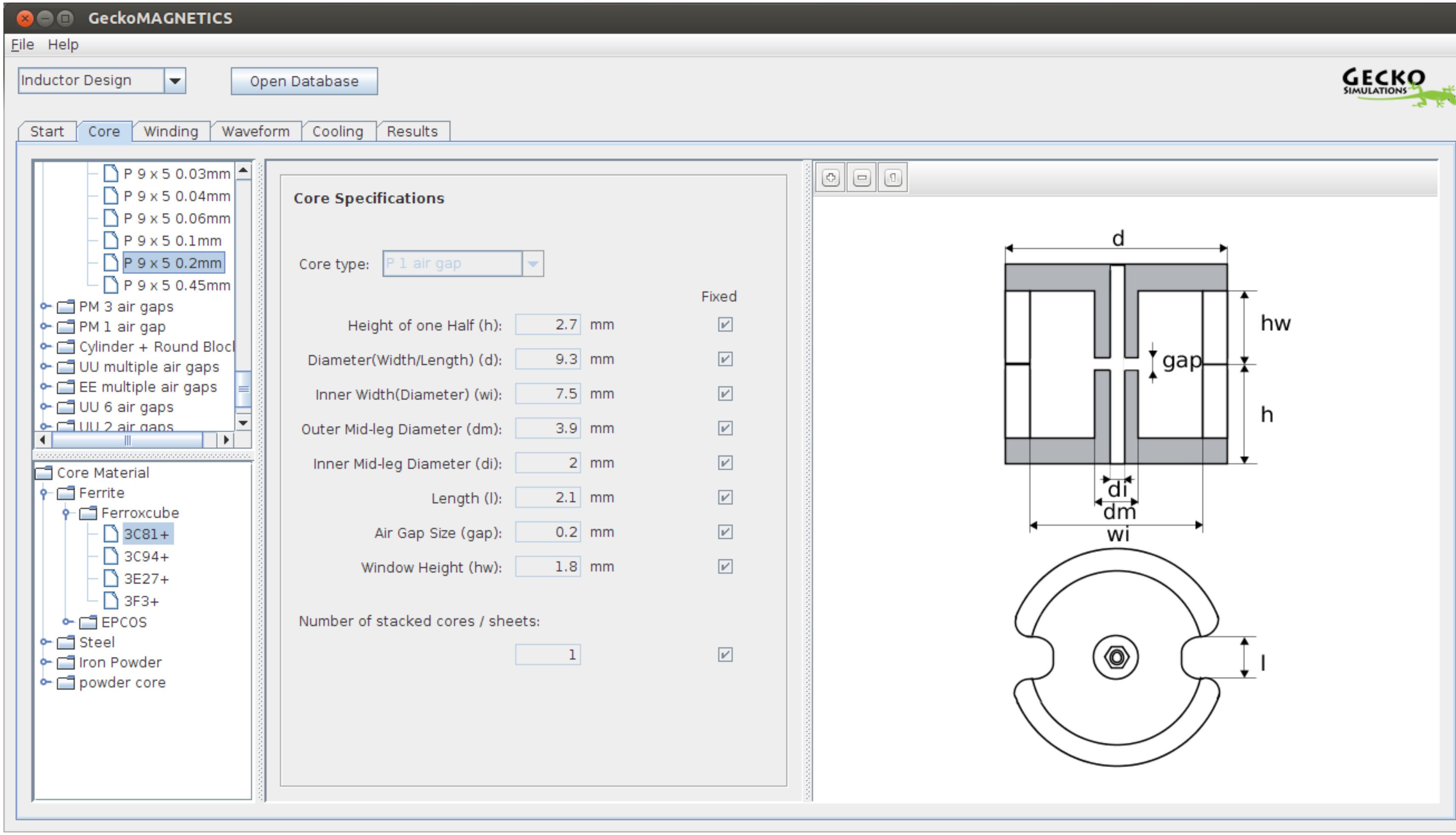
user selects:
1. Several pre-defined wires (e.g. AWG16) OR
sets the range of wire geometry properties
(Round Wire, Litz, Foil, Rectangular)
(design based on the filling factor
OR diameter of wire)
2. Several Winding Materials



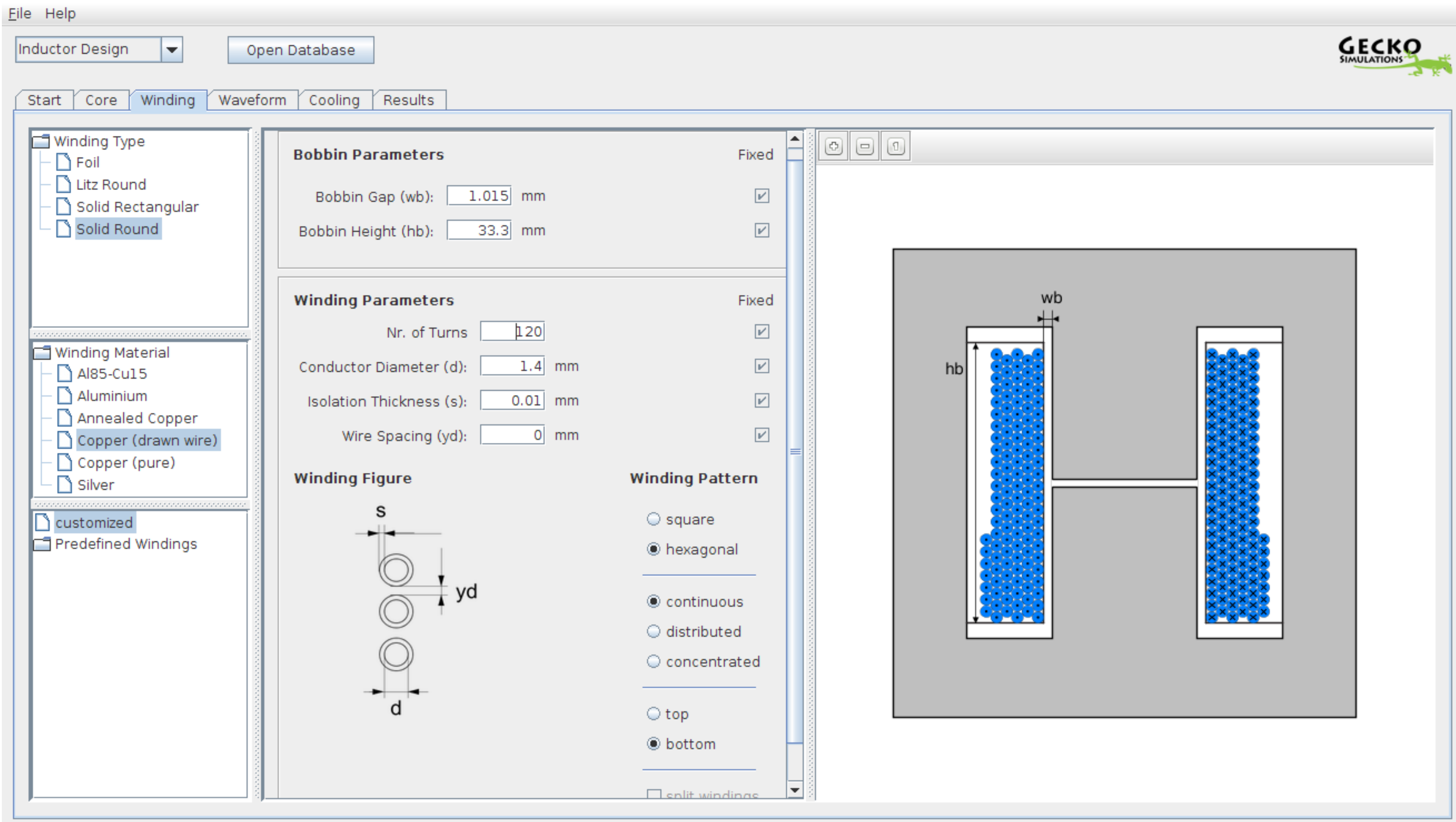
→ n_2 绕组

→ $n_1 \cdot n_2$ 设计

GeckoMAGNETICS
Core Tab

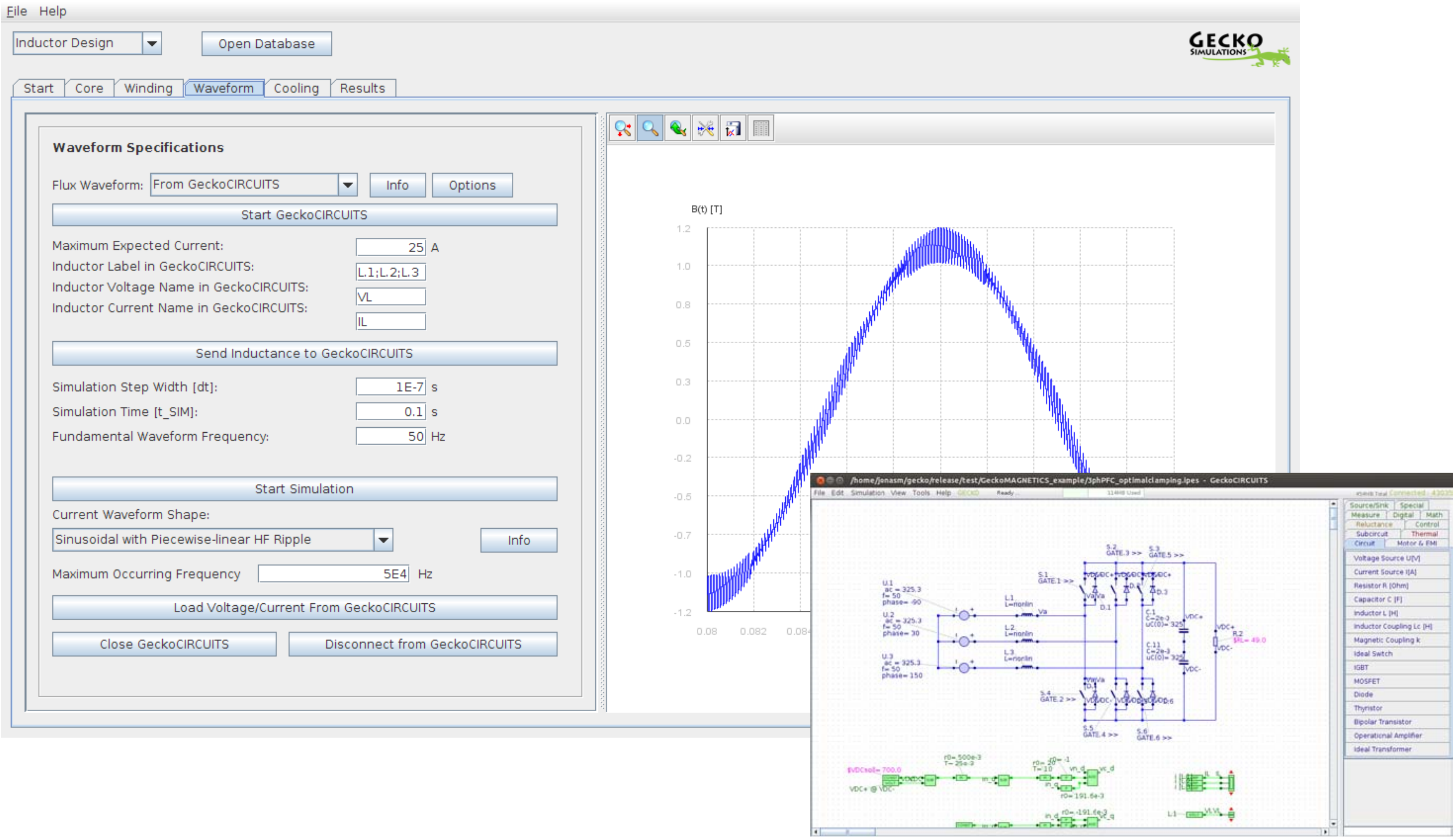


GeckoMAGNETICS
Winding Tab

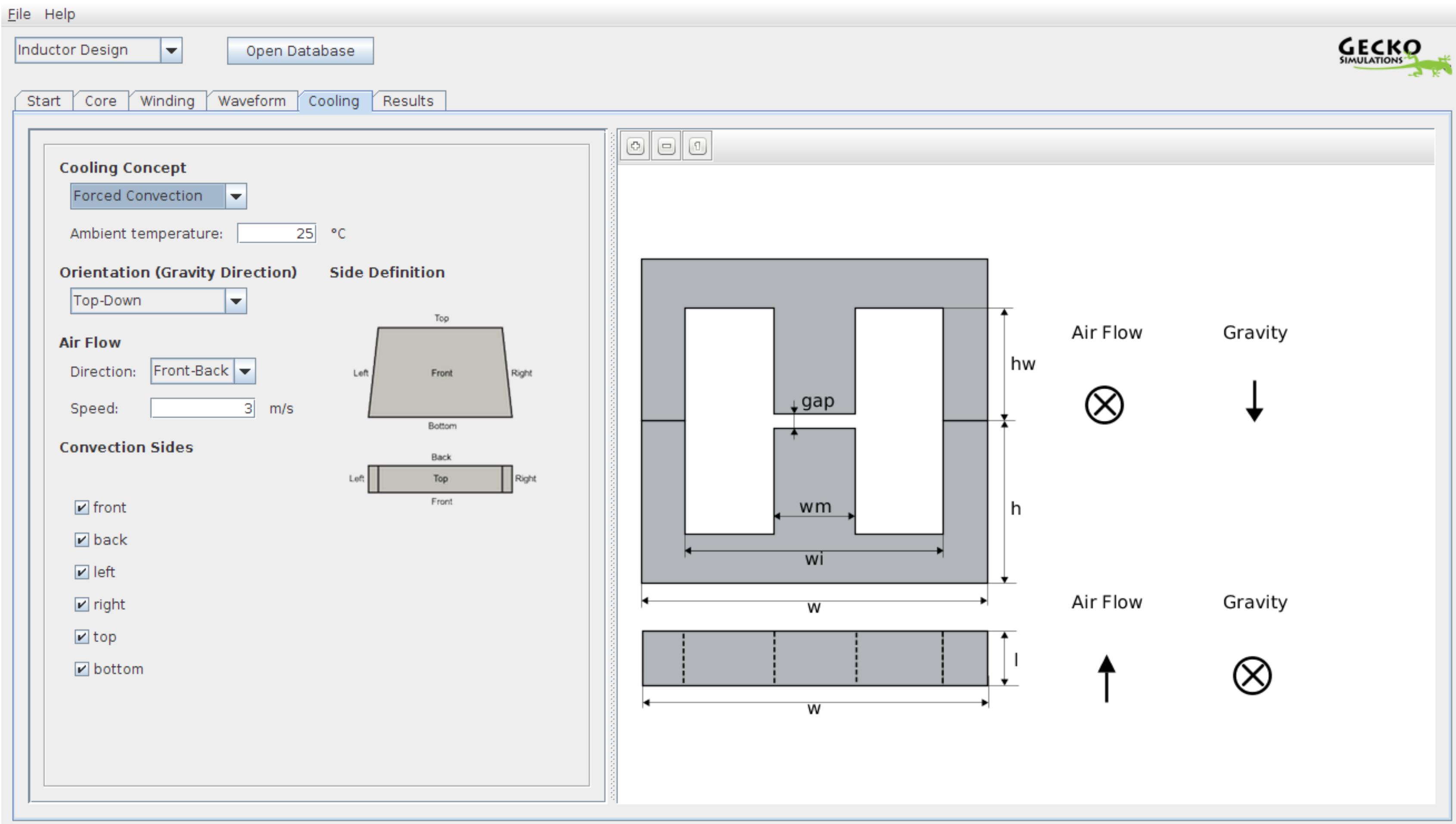


GeckoMAGNETICS

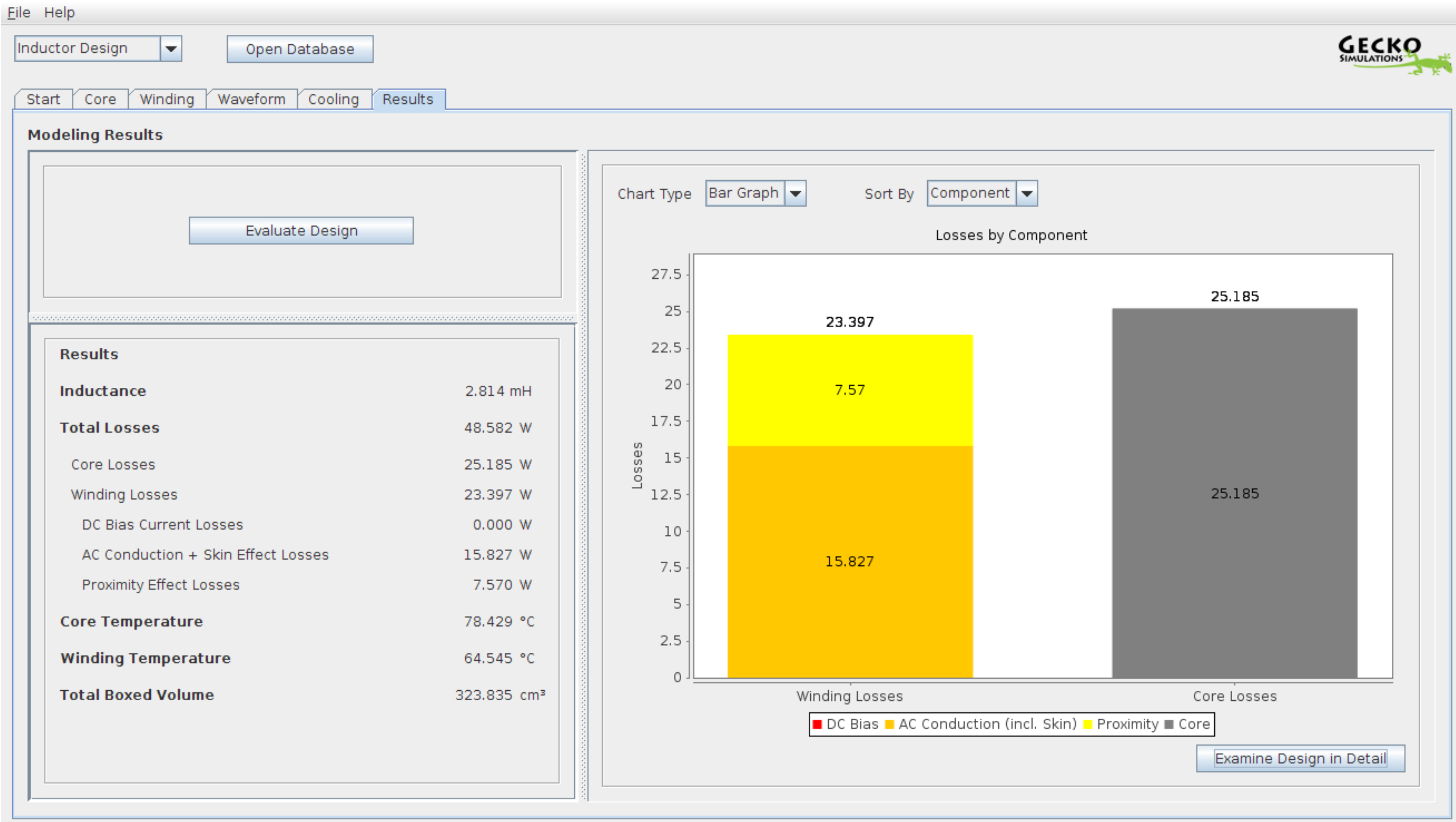
Waveform: Link to GeckoCIRCUITS



GeckoMAGNETICS
Cooling Tab

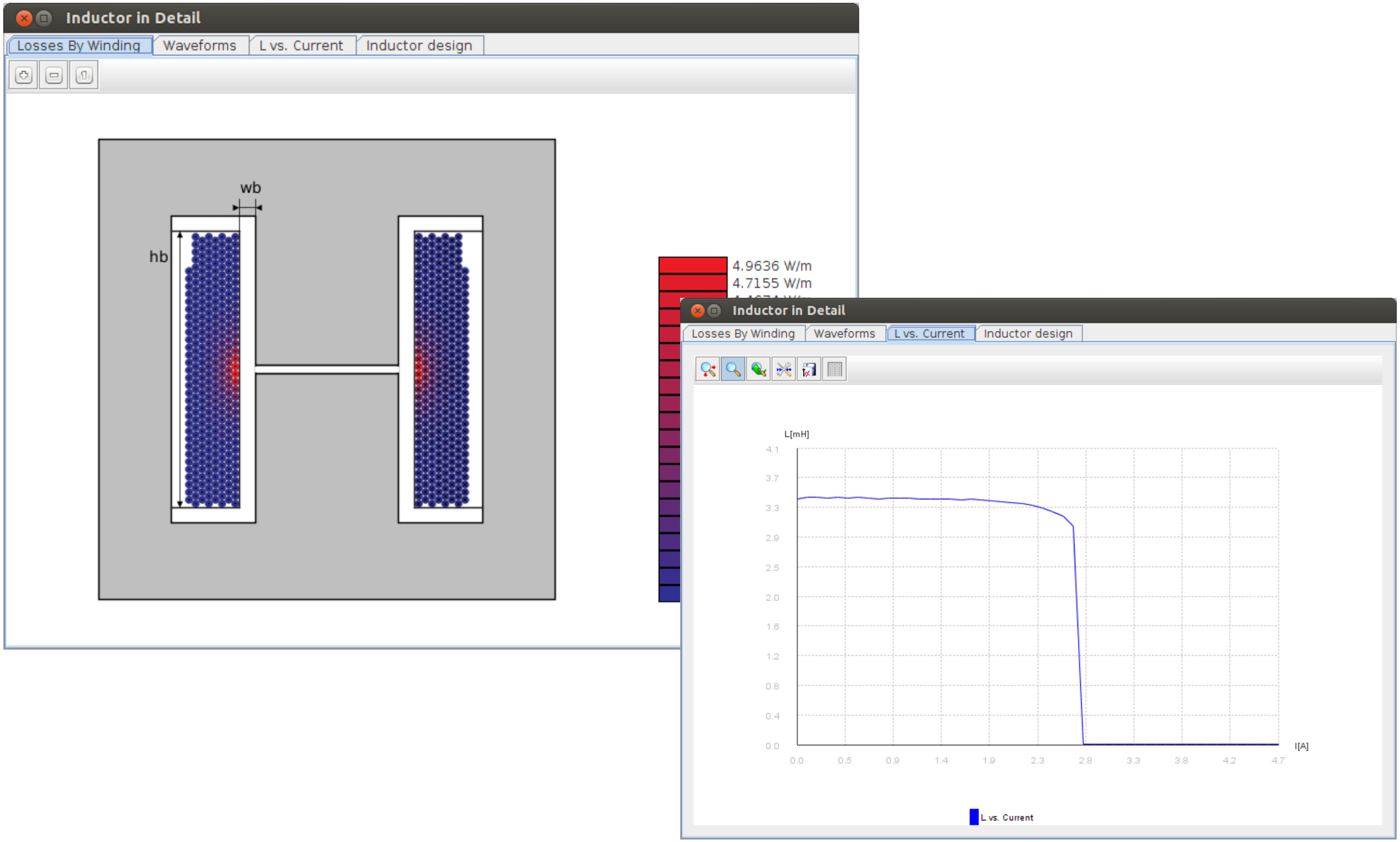


GeckoMAGNETICS
Results Tab (1)

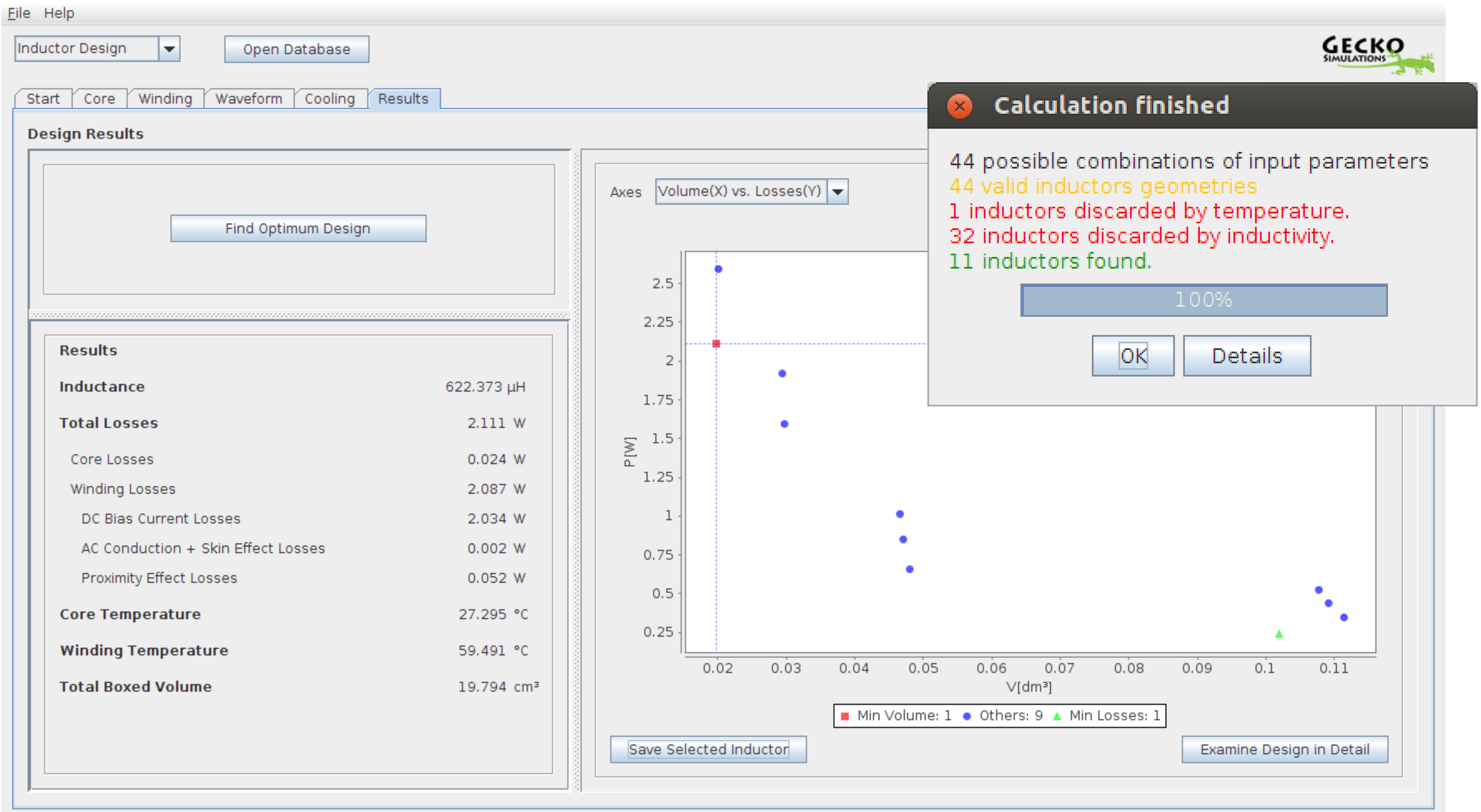


GeckoMAGNETICS

Results Tab (2)



GeckoMAGNETICS
Design Mode



GeckoMAGNETICS - 总结

- 绕组损耗计算手解繁琐，用GeckoMAGNETICS 软件轻松，间接和准确.
- 磁芯损耗计算异常苦难，设计准确程度很大程度上取决于磁芯测量数据
- 软磁材料测量以及在不同激励条件下的损耗特征是准确设计磁器件的关键!

Gecko-Simulations AG, Zurich, Switzerland

Further information at www.gecko-simulations.com

Email: contact@gecko-simulations.com

部分使用我们软件的顾客:

谢谢！

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