



此培训资料来源于德州仪器（TI）和中国电源学会（世纪电源网）合作举办的“TI 现场培训”课程，世纪电源网同意在 TI 网站上分享这些文档。



福州大学  
FUZHOU UNIVERSITY



# 第一讲

## 电磁场基本概念与电磁兼容

主讲：陈为 博士

福州大学电气工程与自动化学院 教授

中国电源学会常务理事、磁技术专业委员会主任委员

功率变换器磁元件技术系列讲座  
2015年3月

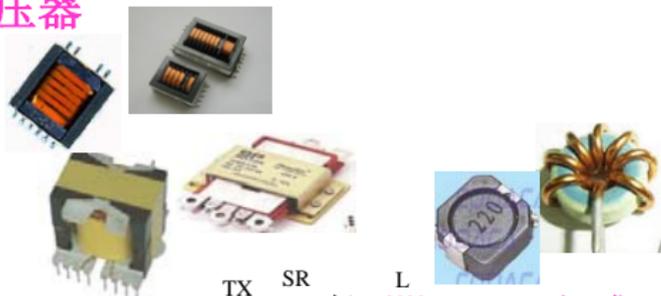
# 主要内容

---

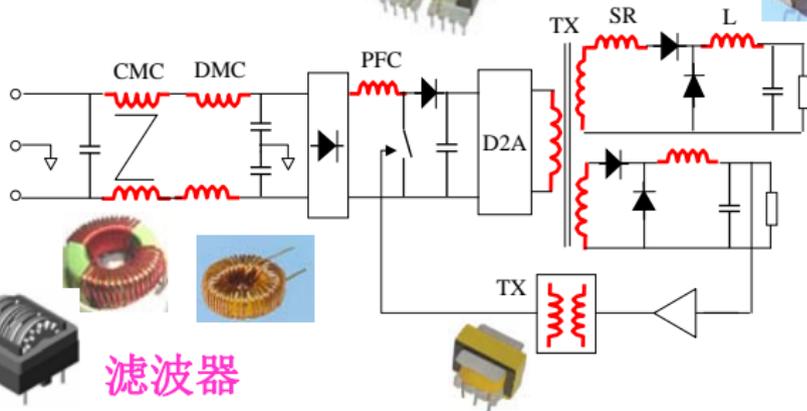
- 功率变换器中的磁性元件及其重要性
- 电磁场基础及磁元件电磁场特性
- 电、磁场的耦合效应
- 电、磁的屏蔽方法

# 功率变换器中的磁性元件

变压器



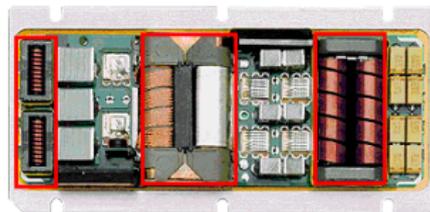
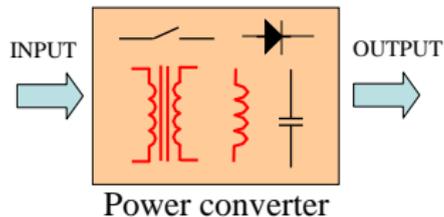
电感器



滤波器



# 磁性元件的重要性和所面临的挑战



Magnetics are critical for:

- ❖ Size and weight
- ❖ Form factor
- ❖ Power loss
- ❖ Manufacture cost
- ❖ Temperature rise
- ❖ Performance

EMI, RFI, Cross-regulation,  
Acoustic noise, Control, etc

- ❖ 高频磁性元件/磁技术已经成为功率变换器进一步发展的瓶颈
- ❖ 磁技术的应用/专利/设计已经成为当前开关电源主要竞争内容

# 绿色电源要求

Product

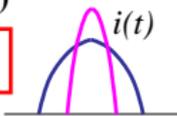


环境保护要求



(IEEE519-1992)

谐波电流要求



电磁兼容要求



环保节能

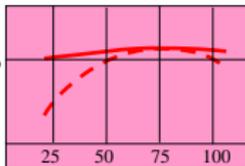


空载损耗要求



负载效率要求

效率  
80%



负载 (%)



CALIFORNIA ENERGY COMMISSION

加州综合效率

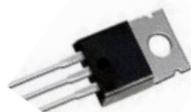
# 磁元件对变换器效率特性的影响



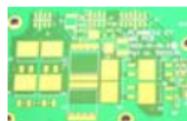
控制芯片



开关器件



二极管



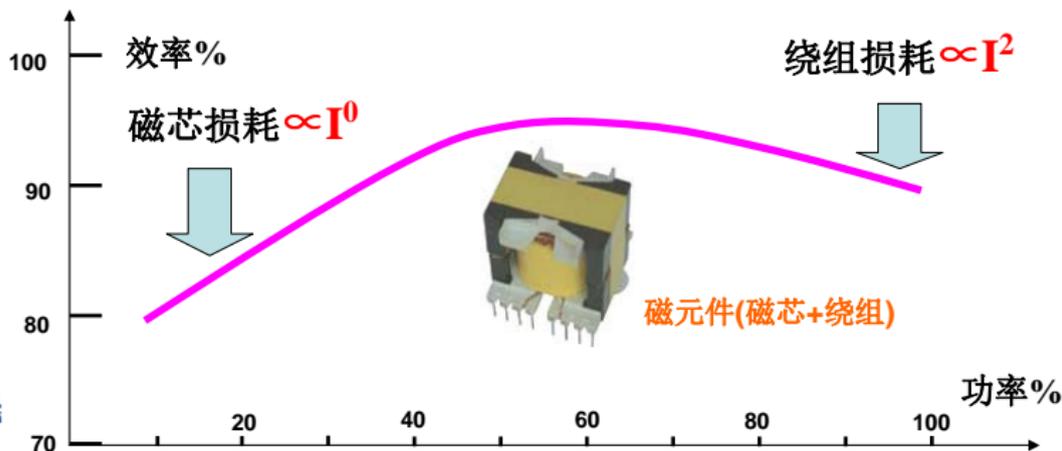
PCB



电容



磁元件



❖ 磁元件损耗特性对变换器效率和节能规范具有重要影响

# 磁性元件的全面设计考虑



结构设计

电气设计

杂散参数

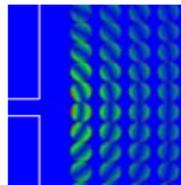
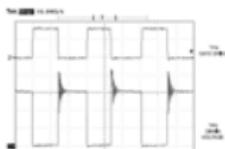
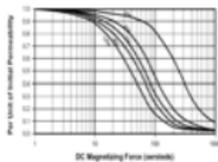
损耗设计

温升设计

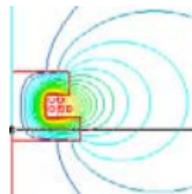
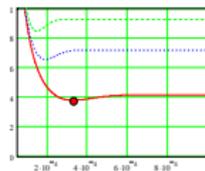
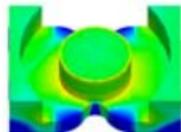
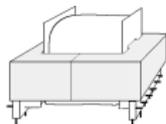
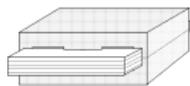
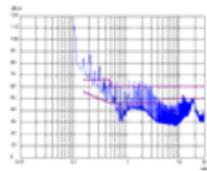
EMI设计



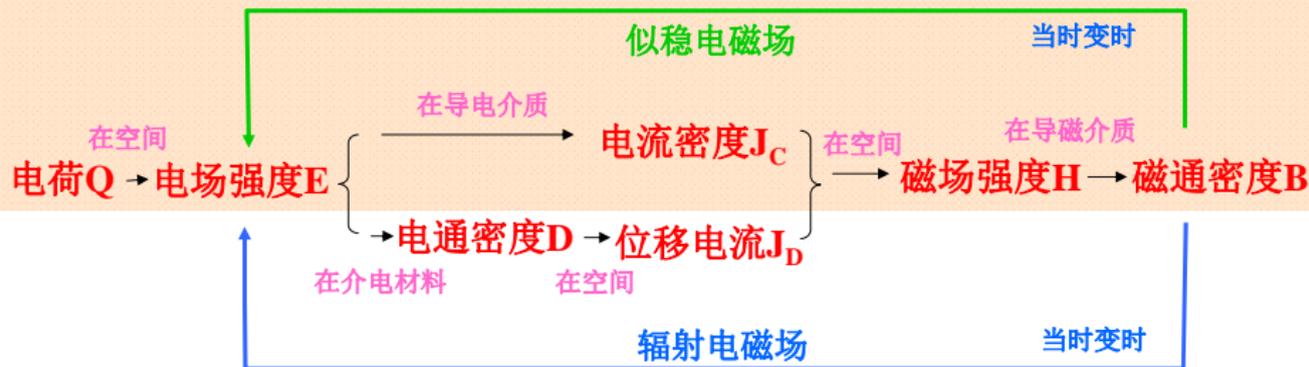
$$L = \frac{\mu \cdot N^2 A_e}{l_e}$$



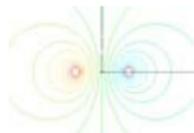
$$\Delta T = \left(\frac{P}{S}\right)^{0.833}$$



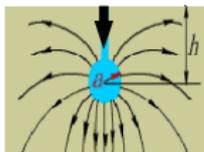
# 电磁场的类型



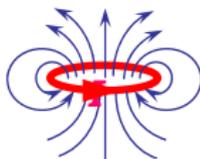
静电场



恒定电流场



静磁场



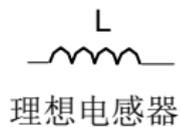
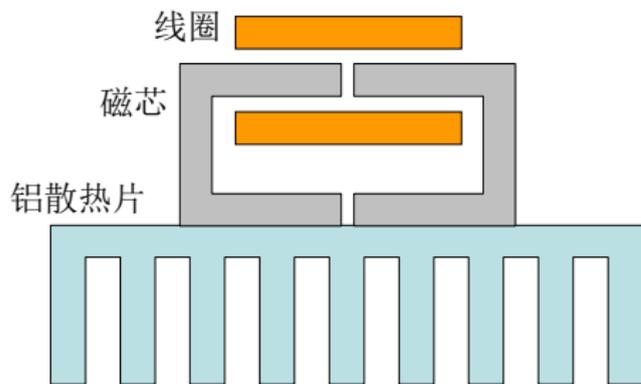
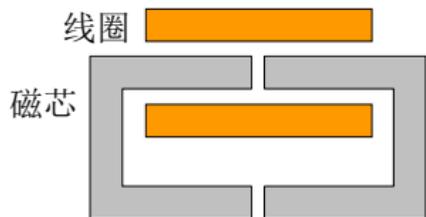
涡流场



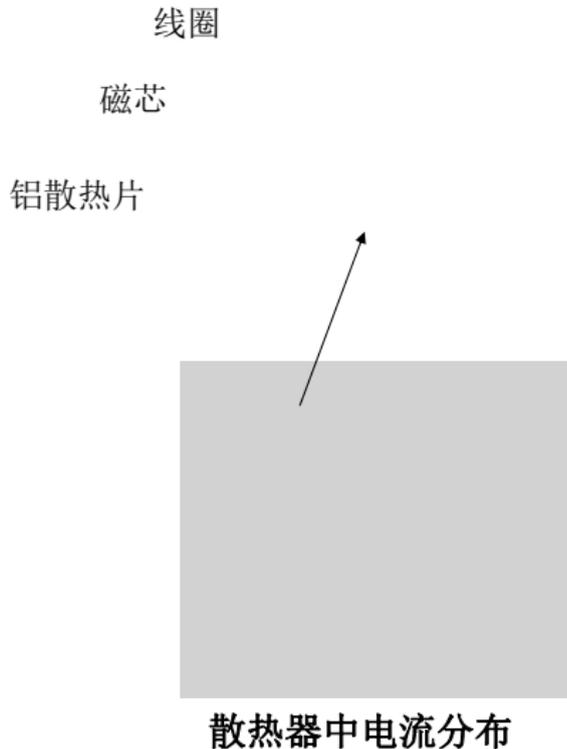
电磁波



# 一个有气隙电感器的磁场分布



# 一个带散热片电感器的磁场和电流密度分布



## 高频涡流效应:

- ❑ 损耗效应: 使得高频损耗增加
- ❑ 去磁效应: 使得高频感量减小

# 工程电磁场基本方程

## Maxwell 电磁场基本方程组

### 微分形式

$$\nabla \times H = J + \frac{\partial}{\partial t} D$$

$$\nabla \times E = -\frac{\partial}{\partial t} B$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = \rho$$

$$D = \varepsilon E$$

$$B = \mu H$$

$$J = \gamma E$$

$$\nabla \times H = J$$

$$\nabla \times E = -\frac{\partial}{\partial t} B$$

$$\nabla \cdot B = 0$$

$$B = \mu H$$

$$J = \gamma E$$

### 积分形式

$$\oint H \cdot dl = I$$

$$\oint E \cdot dl = -\iint \frac{dB}{dt} \cdot dS$$

$$\oiint B \cdot dS = 0$$

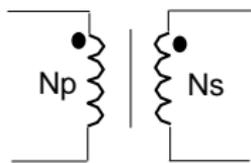
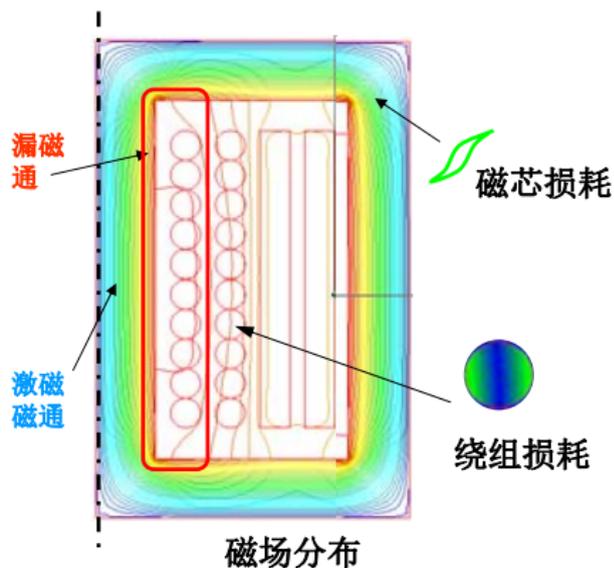
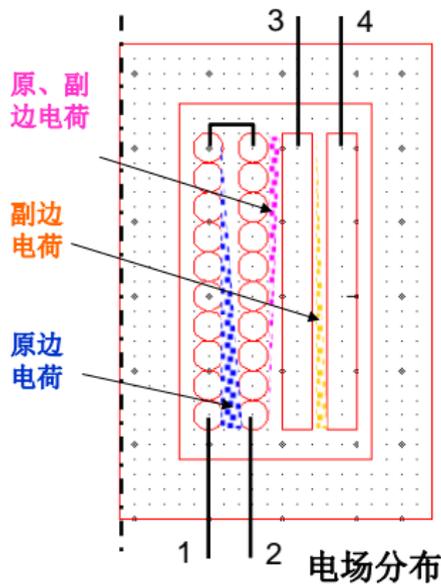
### 物理定律

安培环路定律

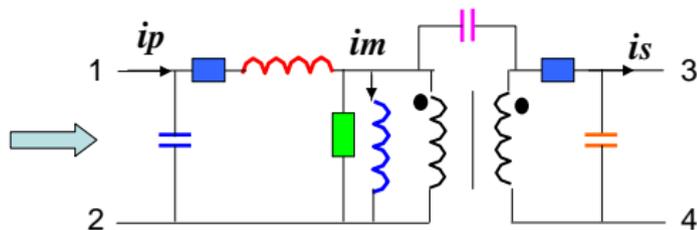
法拉第定律

磁通连续性定理

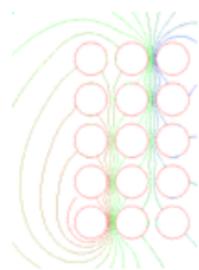
# 变压器电磁场分布特性与等效电路参数



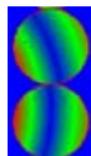
理想变压器



# 电感器中的电磁场分布与集总参数

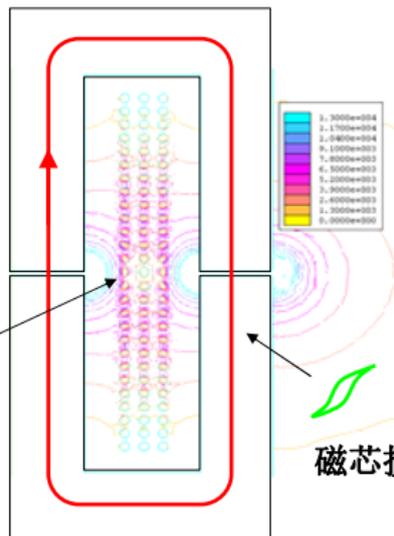


电场

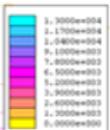


电流场

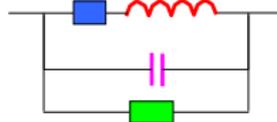
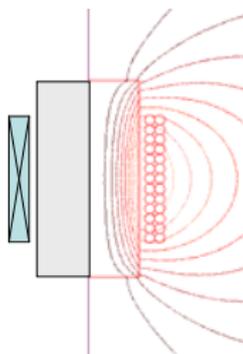
集中磁路磁场



磁芯损耗

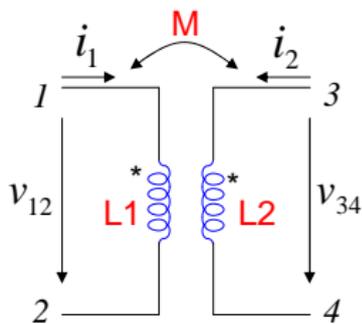
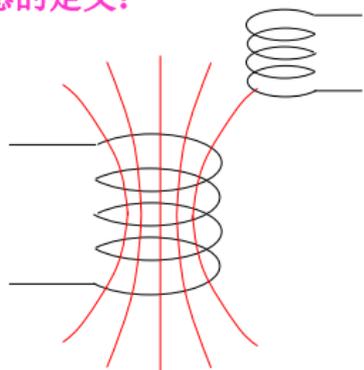


开放磁路磁场



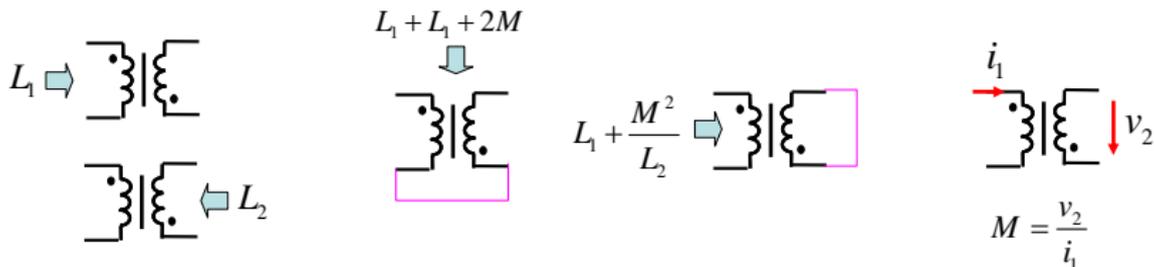
# 磁场耦合——互感

□ 互感的定义:

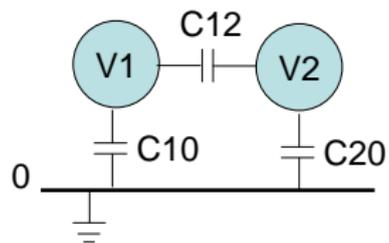


互感模型

□ 互感的测量:



## 电场耦合——部分电容

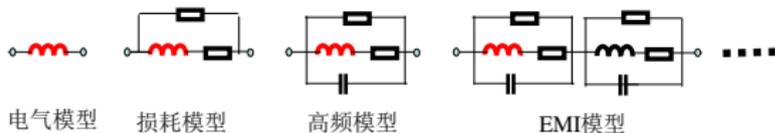


# 磁性元件仿真模型复杂层次

## 磁性元件

内部参数

外部参数

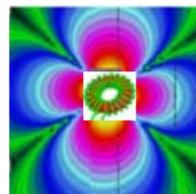
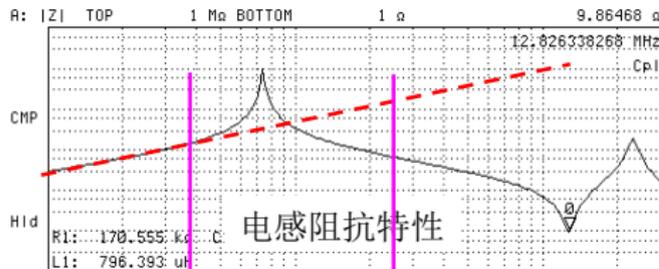


电气模型

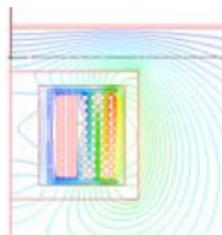
损耗模型

高频模型

EMI模型

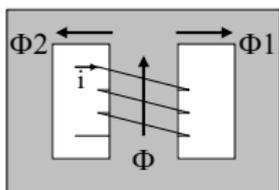


磁场泄漏耦合



电场感应耦合

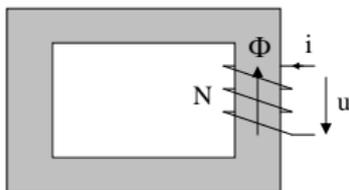
# 磁路及其基本定律



$$\sum \Phi = 0 \quad \text{对各个磁路节点}$$

磁通连续性定理

$$\Phi = \Phi_1 + \Phi_2$$

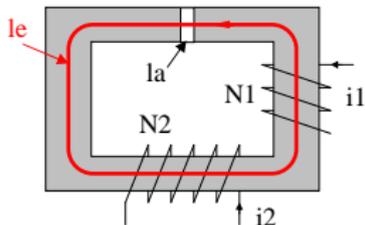


$$u = \frac{d\psi}{dt} = N \cdot \frac{d\Phi}{dt} = N \cdot A_e \cdot \frac{dB}{dt} \quad \text{对各个绕组}$$

法拉第定律

$$\int_{t_0}^t u(t) dt = N \cdot A_e \cdot [B(t) - B(t_0)] = N \cdot A_e \cdot \Delta B |_{(t-t_0)}$$

$$\text{VoltSecond} = N \cdot A_e \cdot \Delta B$$

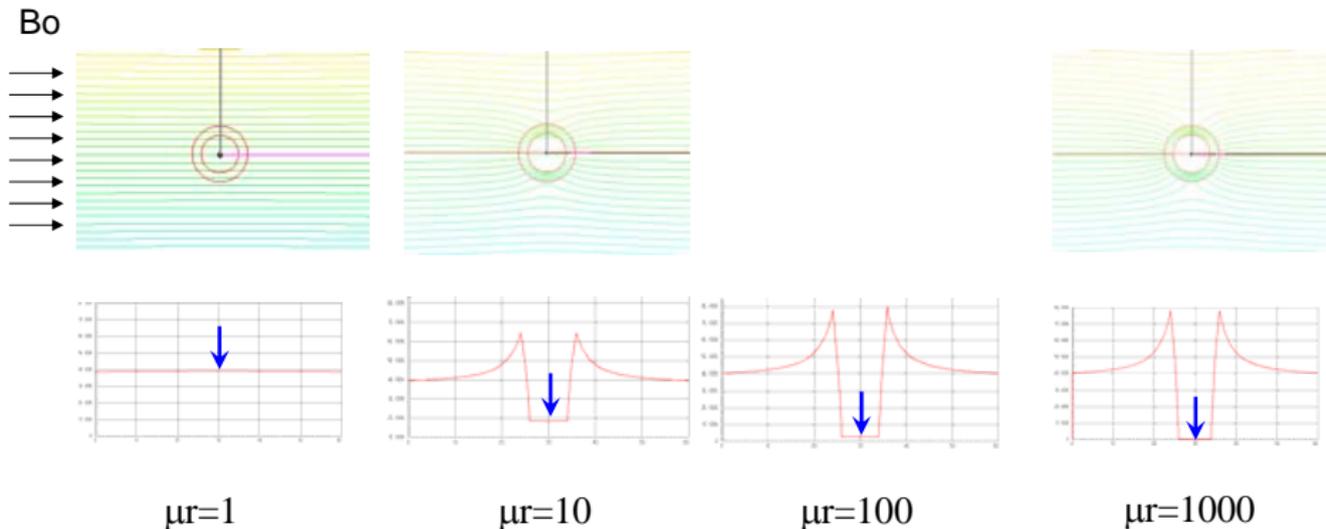


$$\sum i \cdot N = \sum U_m = \sum H \cdot l_e \quad \text{对各个磁回路}$$

安培环路定律

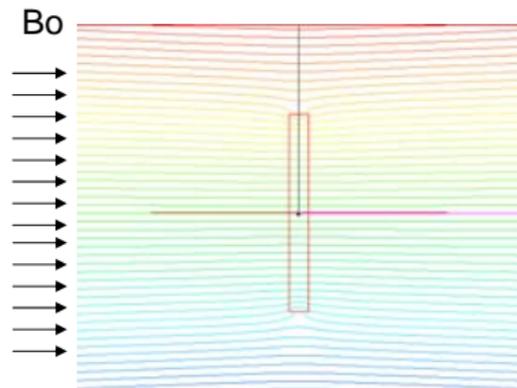
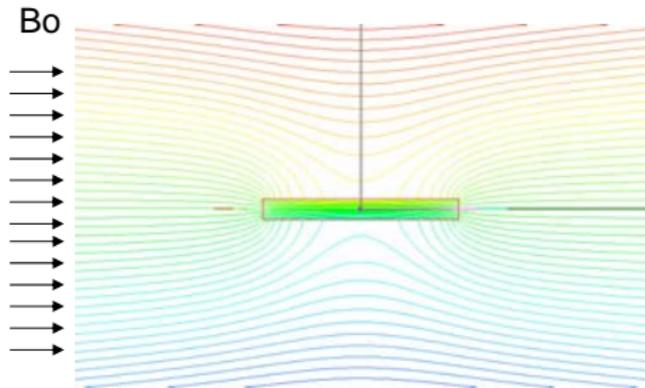
$$i_1 \cdot N_1 + i_2 \cdot N_2 = H_m \cdot l_m + H_a \cdot l_a$$

# 恒定（低频）磁场的屏蔽

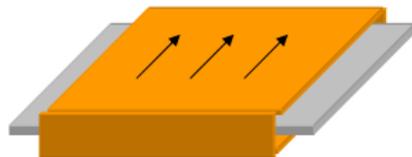
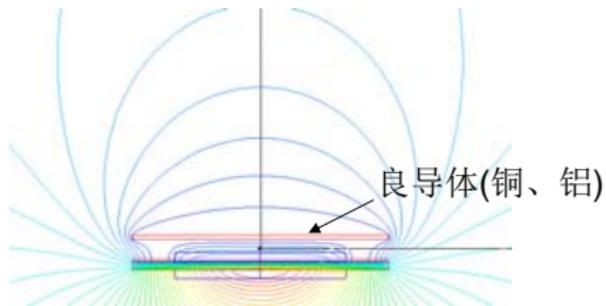
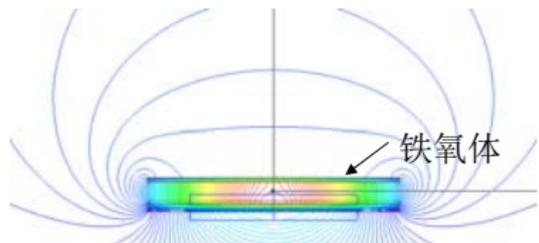
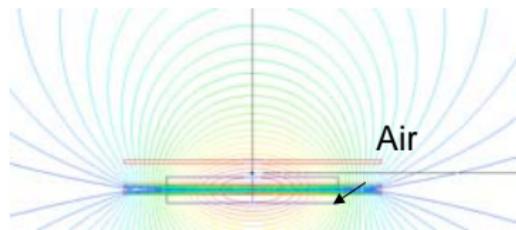


- 屏蔽材料磁导率越高，屏蔽效果越好
- 屏蔽材料厚度越厚，屏蔽效果越好

# 恒定（低频）磁场的局部减弱



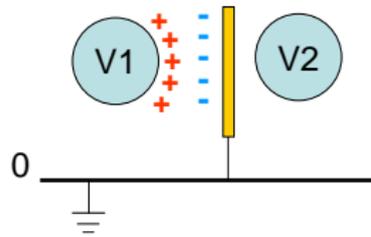
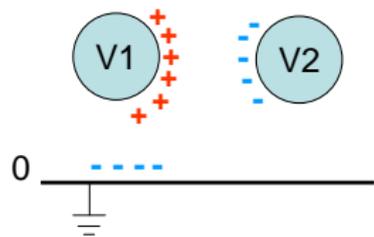
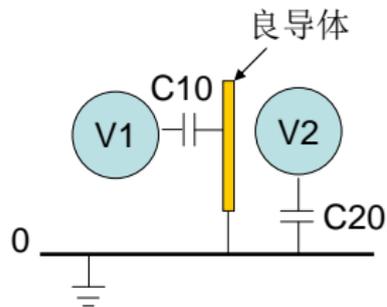
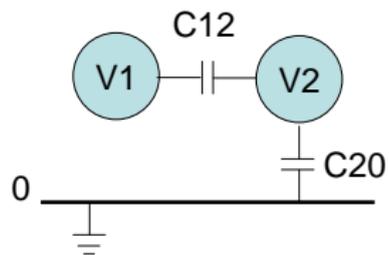
# 高频磁场的屏蔽方式



- 电感量增加
- 重量大
- 损耗不增加很大

- 电感量降低
- 重量轻
- 损耗增加很大

# 电场的屏蔽





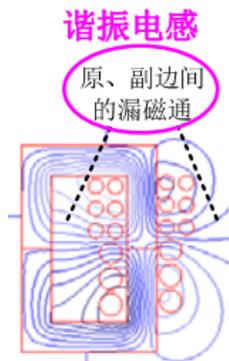
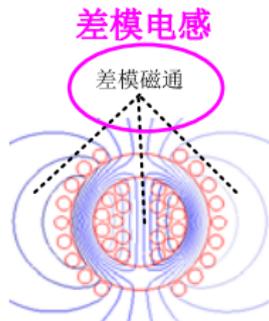
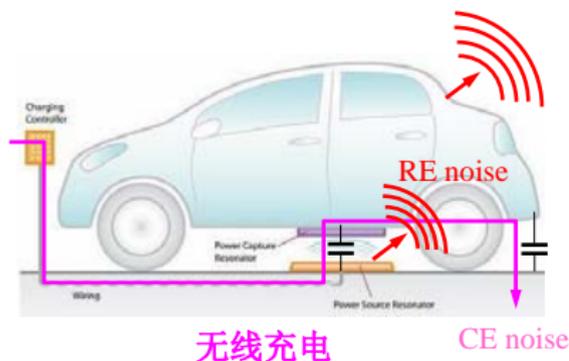
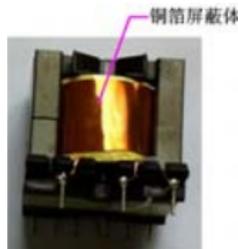
# 仅屏蔽电场而不屏蔽磁场的方法

磁性元件由于体积大，其对地电场耦合较大。一般采用法拉第电场屏蔽技术。

✓ 优点：有效屏蔽电场

✓ 缺点：

- ① 高频磁场也被屏蔽，从而改变磁件磁性参数；
- ② 由于箔状导体涡流效应，产生较大的损耗。



❑ 传统箔状电场屏蔽体会影响某些磁件的磁性参数，不适用于一些对磁性杂散参数有特殊要求的场合。

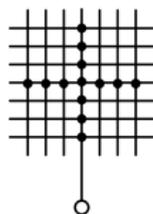
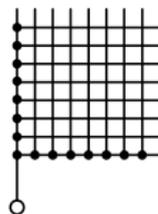
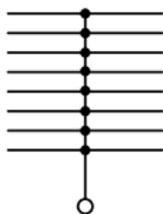
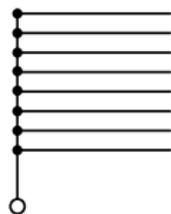
# 梳状电屏蔽体

梳状电场屏蔽体的原理结构：



- 由若干根金属导线组成梳状或网状；
- 在每根导体上各取一个点连接起来，且不构成电回路。

梳状电场屏蔽体可能的连接结构：



□ 只屏蔽电场,不屏蔽磁场,即对磁场分布/磁性参数没有影响



福州大学  
FUZHOU UNIVERSITY



谢谢!  
Q & A