



福州大学  
FUZHOU UNIVERSITY



# 高频磁性元件与磁性材料

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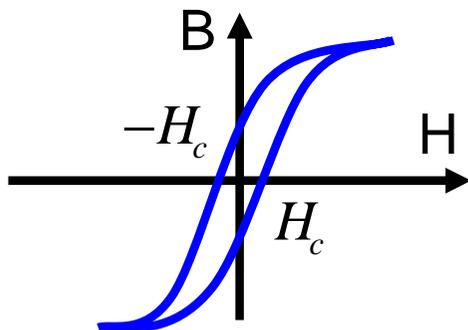
# 主要内容

- 磁性材料的分类
- 软磁材料的主要参数和特性
- 高频磁性元件对磁材特性的要求
- 主要的高频磁性材料及其特点
- 磁性材料的损耗测量
- 磁性材料的发展



# 磁性材料的分类

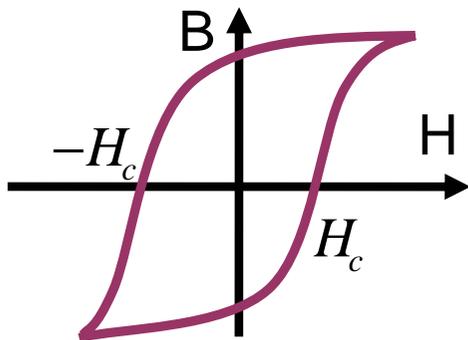
## 软磁材料



$\mu_r$ 大，易磁化、易退磁（起始磁化率大）。饱和磁感应强度大，矫顽力( $H_c$ )小，磁滞回线的面积窄而长，损耗小（ $HdB$ 面积小）。

导磁作用，用于继电器、电机、以及各种功率变换器高频磁件的磁芯。

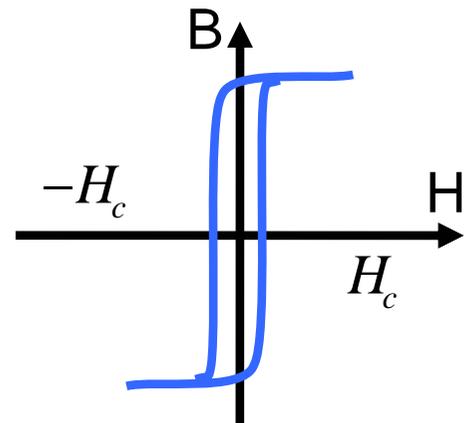
## 硬磁材料



矫顽力( $H_c$ )大 ( $>10^2 A/m$ )，剩磁 $B_r$ 大，磁滞回线的面积大，损耗大。

偏磁作用，磁电式电表、扬声器和永磁电机中永磁铁。

## 矩磁材料



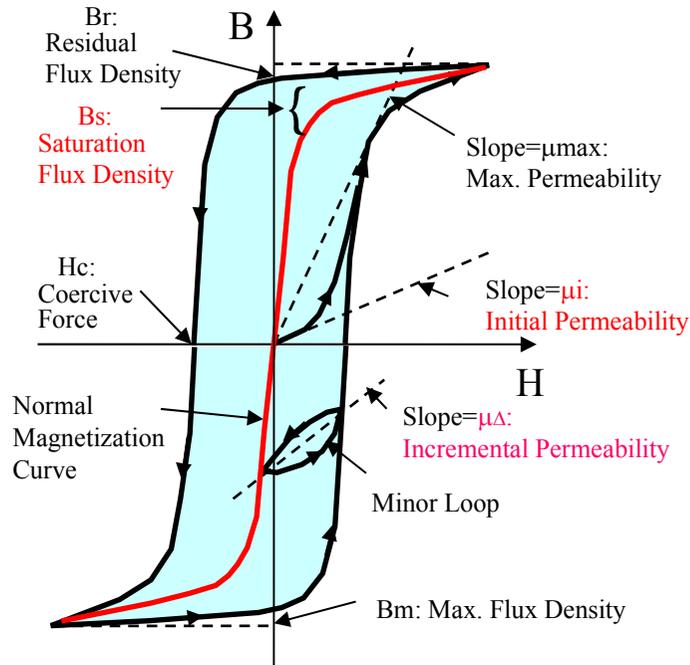
$B_r$ 接近 $B_s$ ， $H_c$ 小，磁滞回线呈矩形，损耗小。

用于两态记忆元件， $+/-$ 脉冲 $H > H_c / H < -H_c$ ，使得磁芯呈 $+B / -B$ 态，可做为二进制的两个态。

做磁放大器(Magamp)磁芯。

# 磁材料的基本参数

## ◆ 电气参数



1) 起始磁导率:  $\mu_i$

$$\mu_i = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H} \Big|_{\Delta H \rightarrow 0}$$

2) 幅值磁导率:  $\mu_a$

$$\mu_a = \frac{1}{\mu_0} \frac{\hat{B}}{\hat{H}}$$

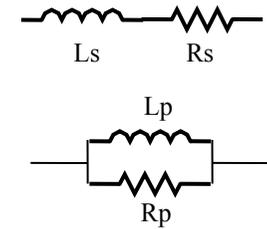
3) 增量磁导率:  $\mu_{\Delta}$

$$\mu_{\Delta} = \frac{1}{\mu_0} \frac{\Delta B}{\Delta H} \Big|_{H_{DC}}$$

4) 复数磁导率:  $\mu_s$

$$\mu_s = \mu'_s - j\mu''_s$$

$$\frac{1}{\mu_p} = \frac{1}{\mu'_p} - j \frac{1}{\mu''_p}$$



## ◆ 损耗参数

$$P_{CV} = K \cdot f^{\alpha} \cdot B^{\beta} \cdot (C_0 + C_1 \cdot T + C_2 \cdot T^2)$$

## ◆ 机械物理参数

弹性模量, 热伸缩系数, 导热系数等

## ◆ 磁滞伸缩系数

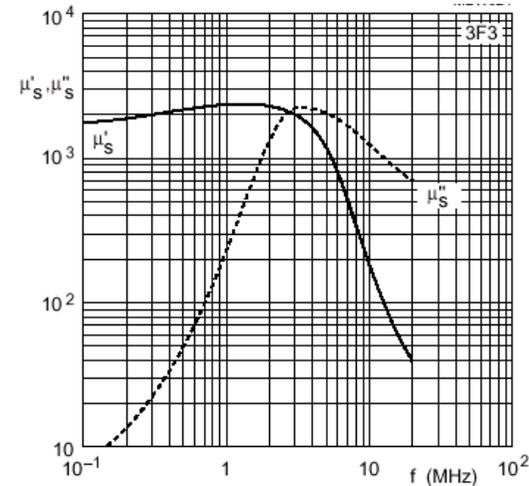
音频噪声的主要来源

# 磁性材料的电气特性参数

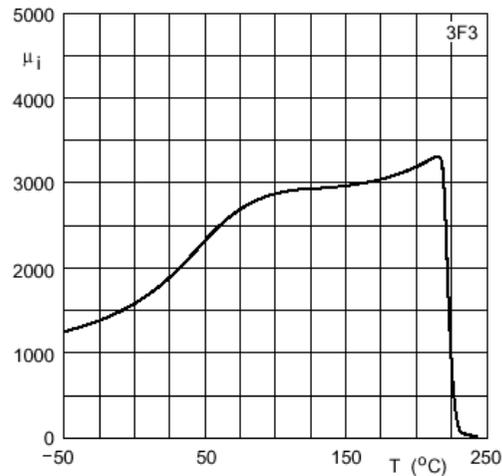
## Ferrite-3F3

### 3F3 SPECIFICATIONS

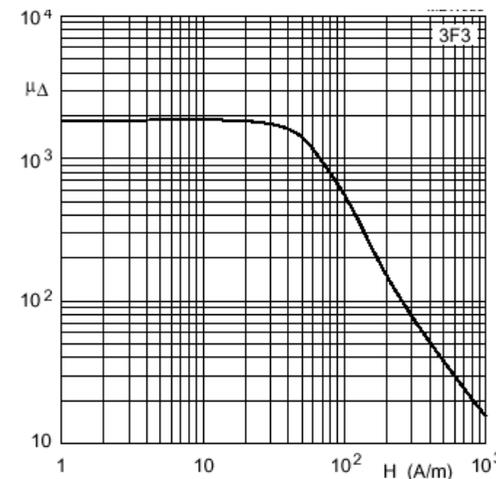
SYMBOL	CONDITIONS	VALUE	UNIT
$\mu_i$	25 °C; $\leq 10$ kHz; 0.1 mT	1800 $\pm 20\%$	
$\mu_a$	100 °C; 25 kHz; 200 mT	$\approx 4000$	
B	25 °C; 10 kHz; 250 A/m	$\geq 400$	mT
	100 °C; 10 kHz; 250 A/m	$\geq 330$	mT
P <sub>v</sub>	100 °C; 100 kHz; 100 mT	$\leq 80$	kW/m <sup>3</sup>
	100 °C; 400 kHz; 50 mT	$\leq 150$	kW/m <sup>3</sup>
$\rho$	DC; 25 °C	$\approx 2$	$\Omega\text{m}$
T <sub>C</sub>		$\geq 200$	°C
density		$\approx 4750$	kg/m <sup>3</sup>



Complex permeability with  $fs$

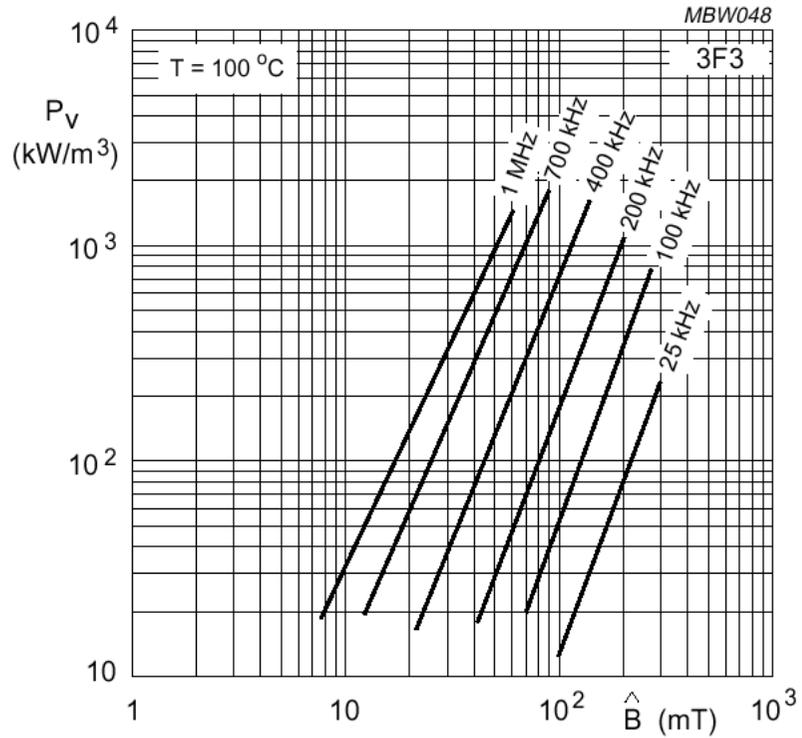


Initial permeability with  $T$

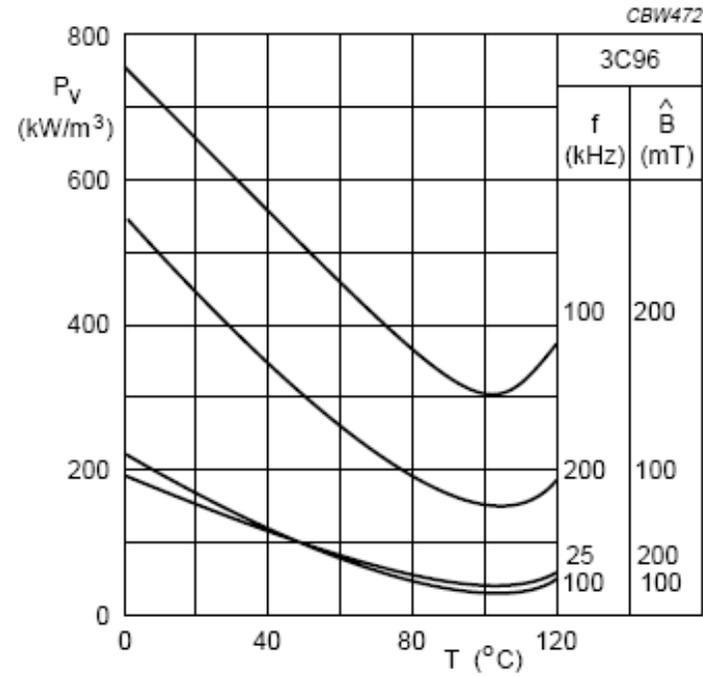


Incremental permeability with  $H_{DC}$

# 磁性材料的损耗特性参数

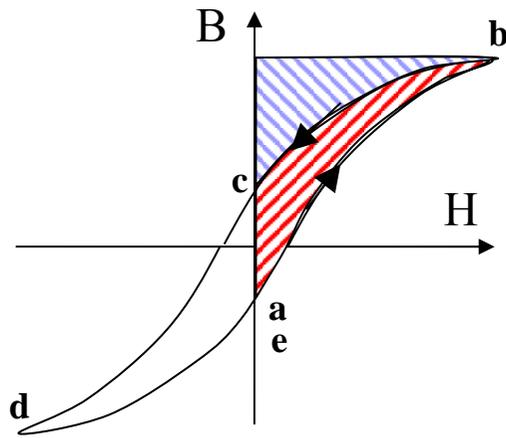


损耗的频率和磁密特性



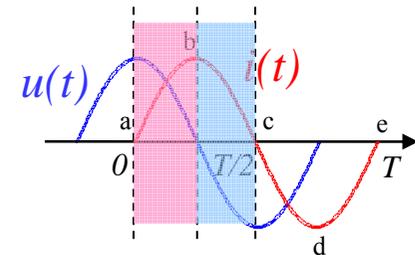
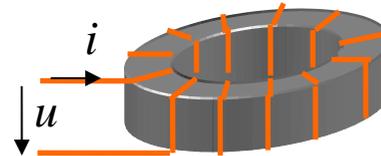
损耗的温度特性 (Ferrite)

# 铁芯的损耗 (磁滞损耗)



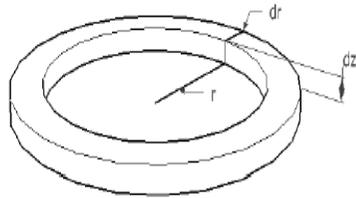
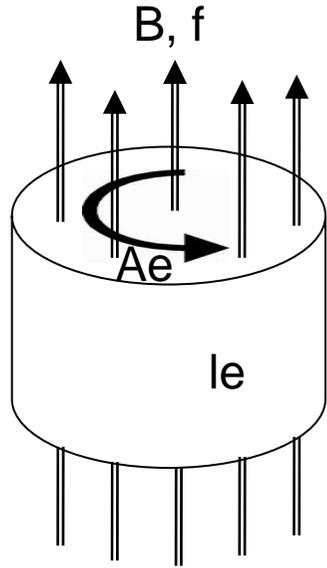
$$P_{in} = \int_a^b (i \cdot u) dt = \int_a^b \left( \frac{H \cdot l_e}{N} \right) \cdot \left( NA_e \frac{dB}{dt} \right) dt = A_e \cdot l_e \int_a^b H \cdot dB$$

$$P_{out} = \int_b^c (i \cdot u) dt = A_e \cdot l_e \int_b^c H \cdot dB$$



- 磁滞损耗大小取决于铁磁材料本身的品质
- 磁滞损耗大小与激磁工作频率成正比
- 磁滞损耗大小与磁通密度大小的平方成正比

# 铁芯的损耗 (涡流损耗)



$$U_0 = \frac{d\phi}{dt} = 2\pi f * B * \pi r^2$$

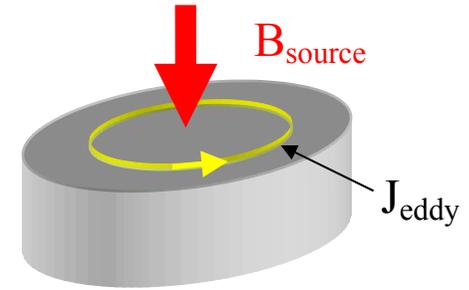
$$dP = \frac{U_0^2}{dR_0} = \frac{4\pi^4 f^2 B^2 r^4}{\rho \frac{l_0}{S_0}} = \frac{4\pi^4 f^2 B^2 r^4}{\rho \frac{2\pi r}{drdz}}$$

$$= \frac{2\pi^3 f^2 B^2 r^3}{\rho} drdz$$

$$P_{eddy} = \iint \frac{2\pi^3 f^2 B^2 r^3}{\rho} drdz = \frac{2\pi^3 f^2 B^2}{\rho} \int_0^{r_{-face}} r^3 dr \int_0^{le} dz$$

$$= \frac{\pi f^2 B^2}{2\rho} Ae^2 le = \frac{\pi}{2} f^2 B^2 le Ae^2 \sigma$$

$$P_{eddy} = \frac{\pi}{2} f^2 B^2 \cdot le \cdot Ae^2 \cdot \sigma$$



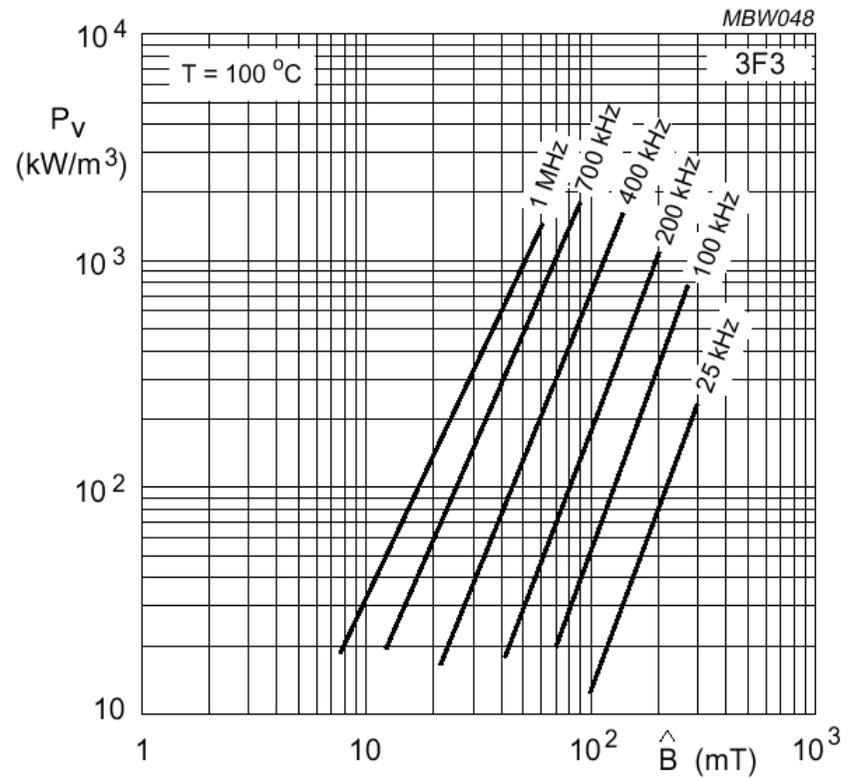
- 涡流损耗大小取决于铁磁材料本身的电导率
- 涡流损耗大小与激磁工作频率的平方成正比
- 涡流损耗大小与磁通密度大小的平方成正比

# 磁芯损耗模型-Steinmetz Model

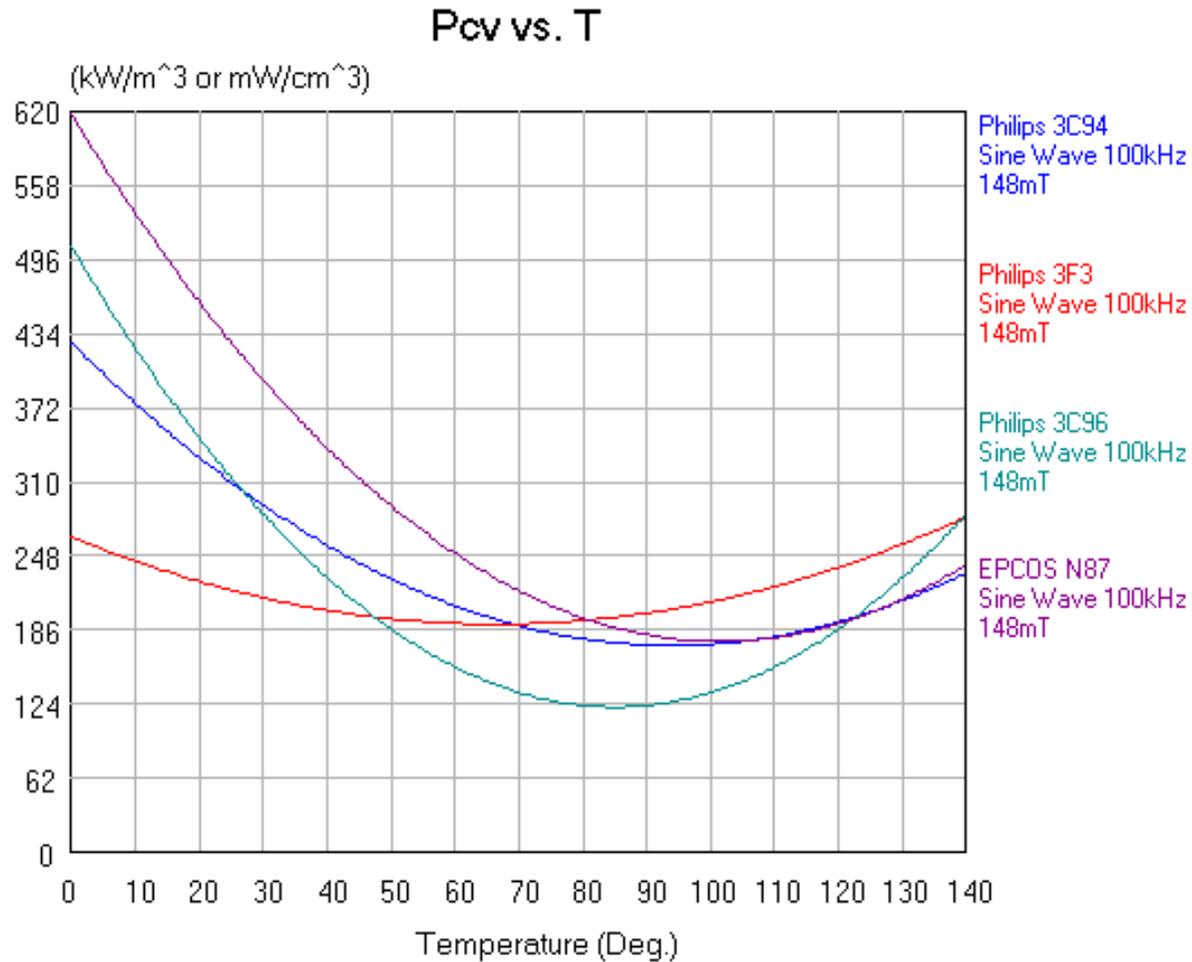
$$P_{CV} = C_m \cdot f^\alpha \cdot B^\beta \cdot (C_0 + C_1 \cdot T + C_2 \cdot T^2)$$

## Core loss is related to:

- ❖ Material grade
- ❖ Frequency
- ❖ Temperature
- ❖ Flux density
- ❖ DC bias
- ❖ Excitation waveform

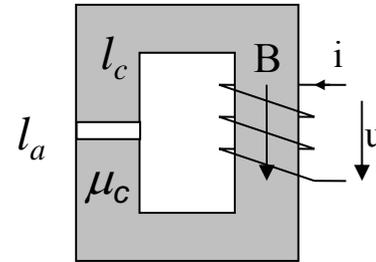
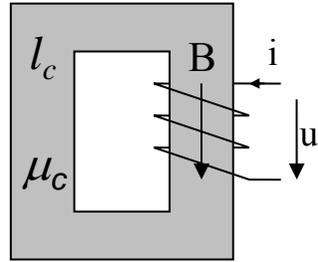


# 磁芯损耗的温度特性

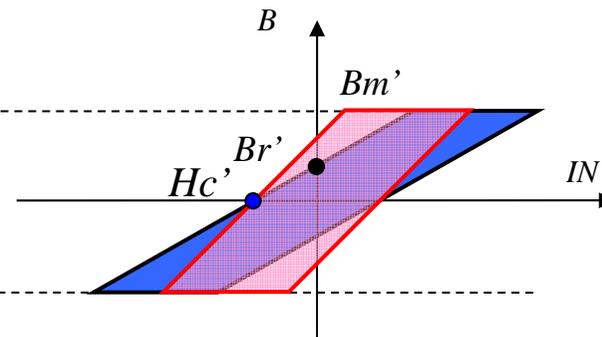
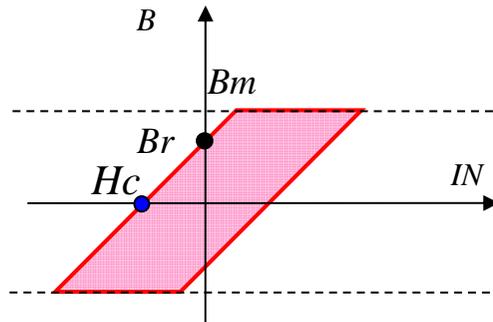


- ◆ 温度对铁氧体的损耗影响很大
- ◆ 不同材料有不同的温度特性曲线
- ◆ 注意设计工作温度的范围

# 磁芯带气隙特性



◆ 磁化曲线



◆ 磁导率

$$\frac{1}{\mu_c}$$

$$\frac{1}{\mu_e} = \frac{1}{\mu_c} + \frac{l_a}{\mu_a \cdot l_c}$$

◆ 剩磁密度

$$B_r$$

$$B_r' = \frac{1}{1 + \frac{l_a}{l_c} \frac{B_r}{H_c} \frac{1}{\mu_0}} = \frac{1}{1 + \frac{l_a}{l_c} \frac{\mu_c}{\mu_0}} = B_r \cdot \frac{\mu_e}{\mu_c}$$

# 磁性材料的性能因子与材料选择

$$P_{thr} = N_p \cdot A_e \cdot I_p \cdot (f \cdot B)$$

$f \cdot B$ : Material performance factor

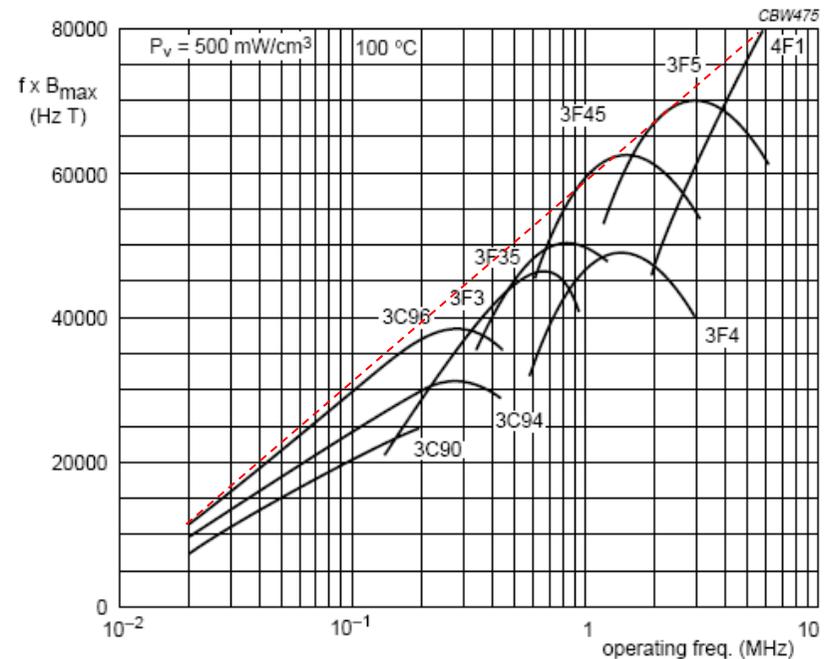
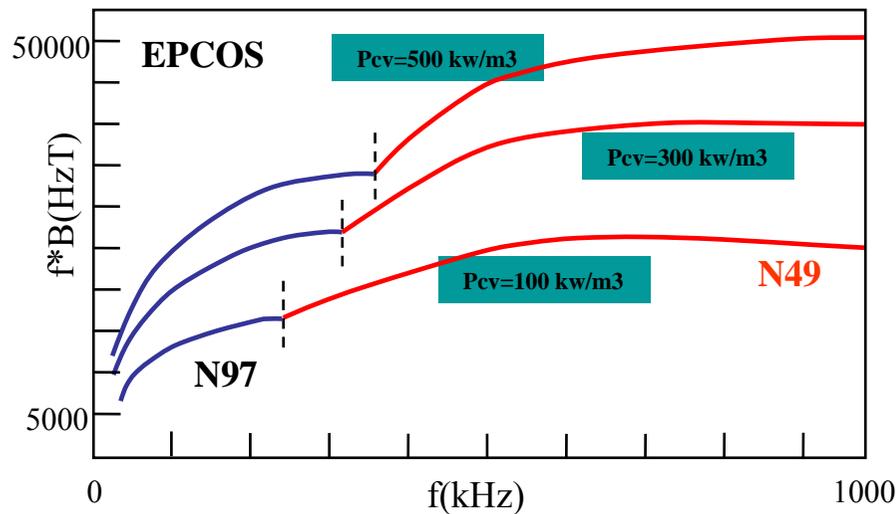
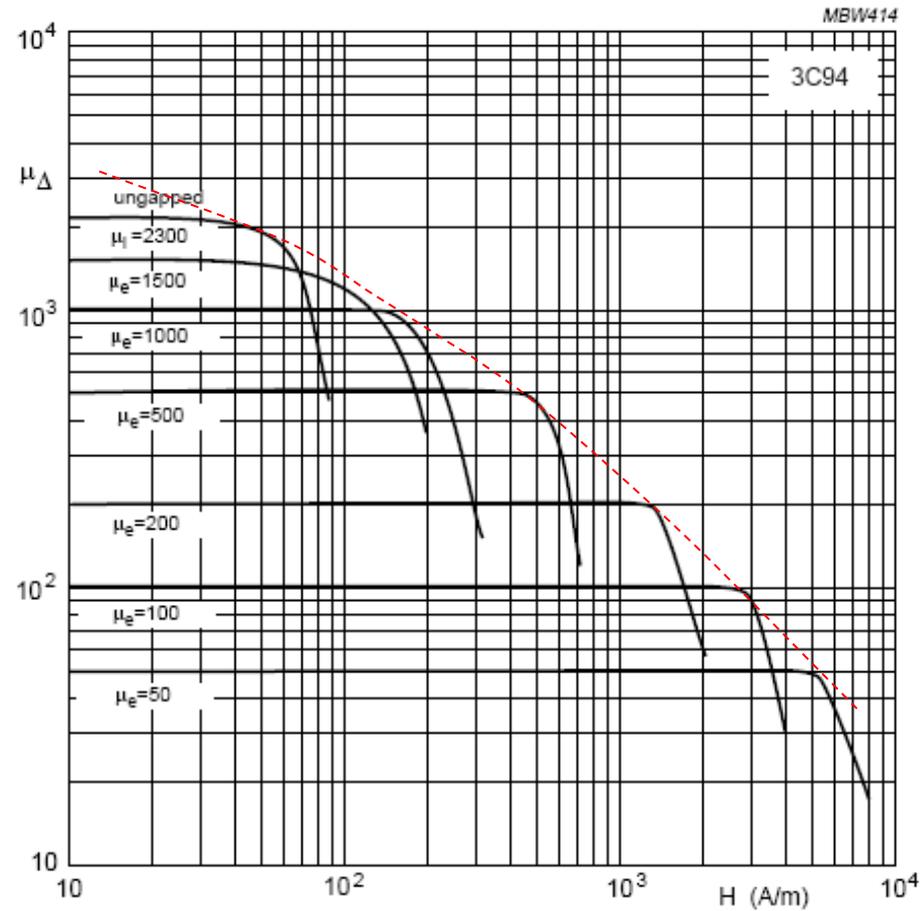
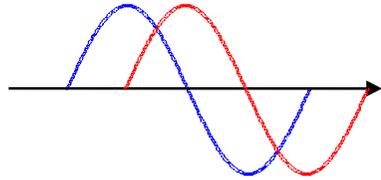


Fig.19 Performance factor ( $f \times B_{max}$ ) at  $P_V = 500 \text{ mW/cm}^3$  as a function of frequency for power ferrite materials.

# 磁性材料的储能特性与材料选择

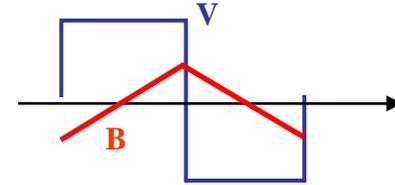


# PWM波形激励下的磁芯损耗



加权平均磁密变化率  $\bar{B}_w$

$$\bar{B}_w = \frac{1}{B_{\max} - B_{\min}} \int_T \left( \frac{dB}{dt} \right)^2 dt$$



$$\bar{B}_{w \sin} = (B_{\max} - B_{\min}) \cdot \frac{\pi^2}{2} \cdot f_{\sin}$$

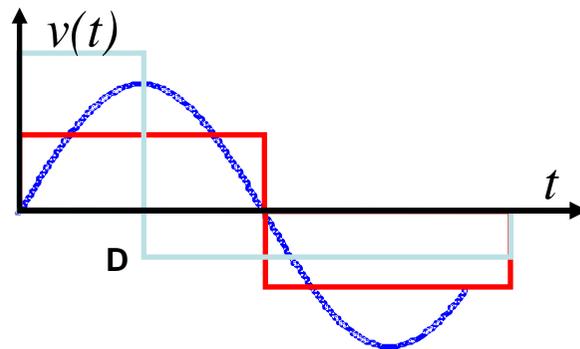


$$\bar{B}_{w \text{arb}} = \frac{1}{(B_{\max} - B_{\min})} \sum_k \frac{(B_{k+1} - B_k)^2}{t_{k+1} - t_k}$$

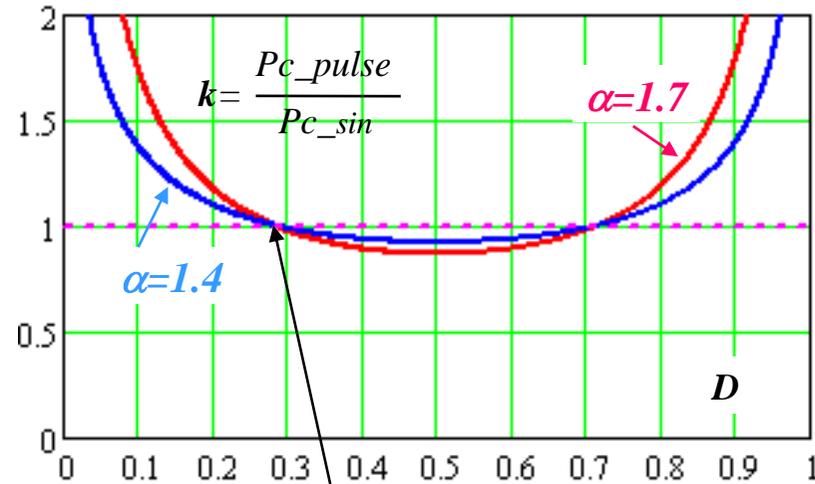
$$f_{\sin} = \frac{2}{\pi^2} \sum_k \left( \frac{B_{k+1} - B_k}{B_{\max} - B_{\min}} \right)^2 \cdot \frac{1}{t_{k+1} - t_k}$$



$$P_c = f_s \cdot C_m \cdot f_{\sin}^{\alpha-1} \cdot B_{ac}^{\beta} \cdot (C_{t0} + C_{t1} \cdot T + C_{t2} \cdot T^2) \cdot V_e$$



Power loss factor,  $k$ , with same  $B_m$  and  $f_s$



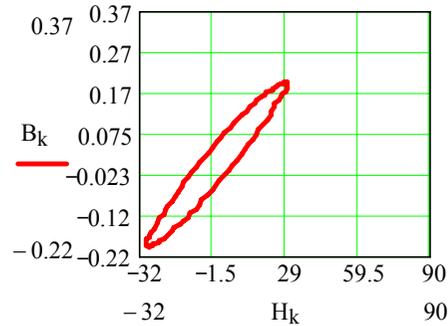
$k=1 @ D=0.283$

# 直流偏磁对磁芯损耗的影响

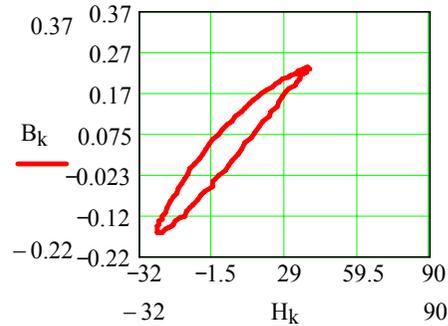
## Core loss model

$$P_c = (1 + K_{1dc} \cdot |B_{dc}| \cdot e^{\frac{|B_{ac}|}{K_{2dc}}}) \cdot K_{1ac} \cdot |B_{ac}|^{K_{2ac}} f_s^{K_{3ac}} \cdot (K_{t1} \tau^2 + K_{t2} \tau + K_{t3})$$

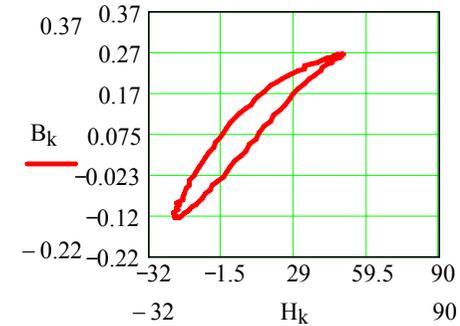
B-H Loop @ fs=100kHz, Bac=200mT, To=100°C



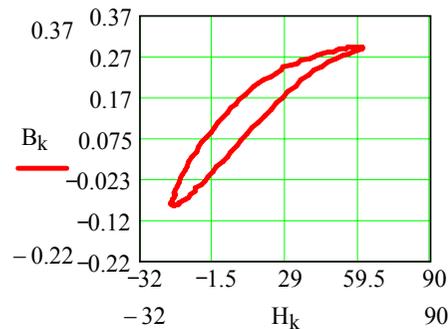
Hdc=0, Pc=504 (kw/m<sup>3</sup>)



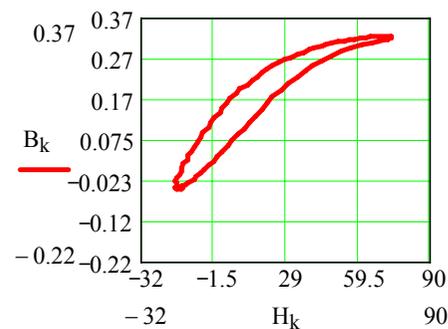
Hdc=6.93A/m, Pc=506 (kw/m<sup>3</sup>)



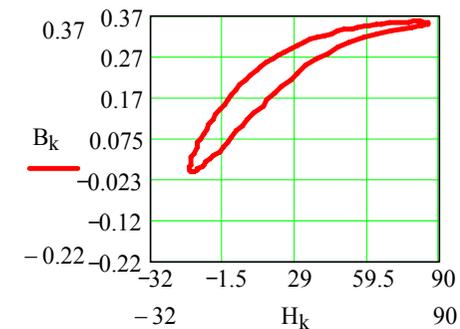
Hdc=13.85A/m, Pc=526 (kw/m<sup>3</sup>)



Hdc=20.77A/m, Pc=584 (kw/m<sup>3</sup>)



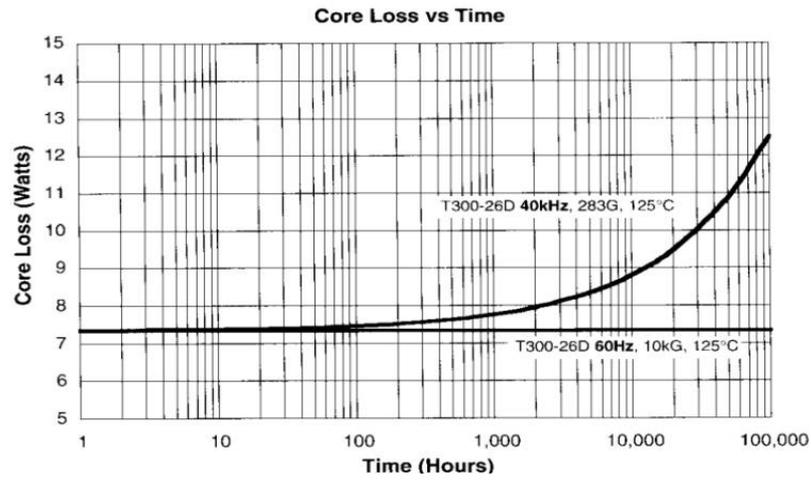
Hdc=27.69A/m, Pc=605 (kw/m<sup>3</sup>)



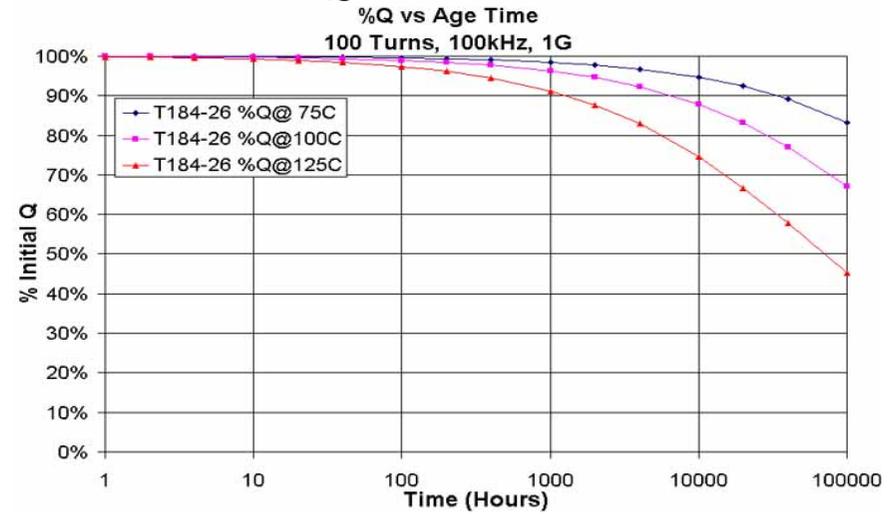
Hdc=34.62A/m, Pc=647 (kw/m<sup>3</sup>)

# 铁粉芯的老化问题

## 铁芯损耗随时间的变化曲线

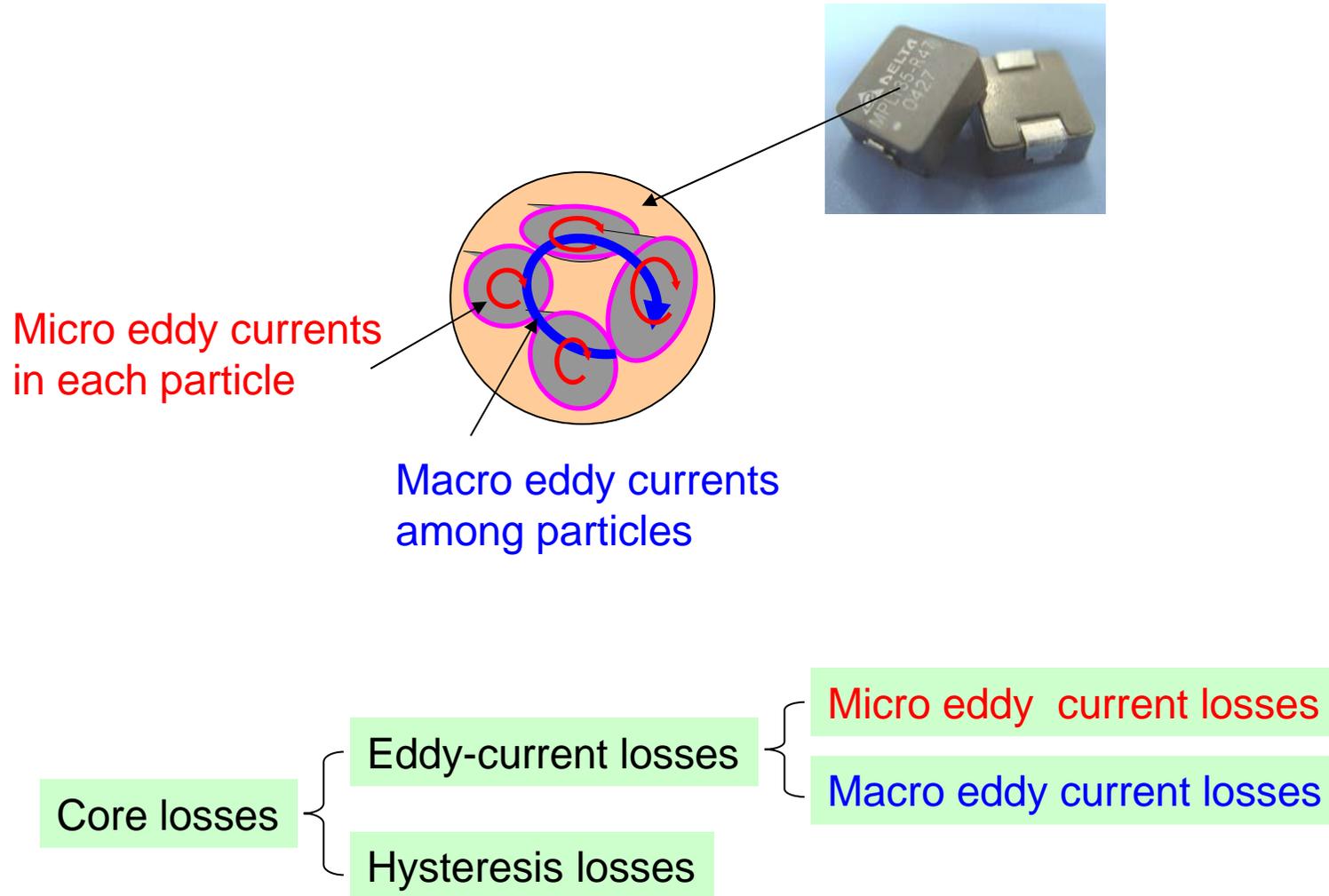


## %Q 随时间变化曲线

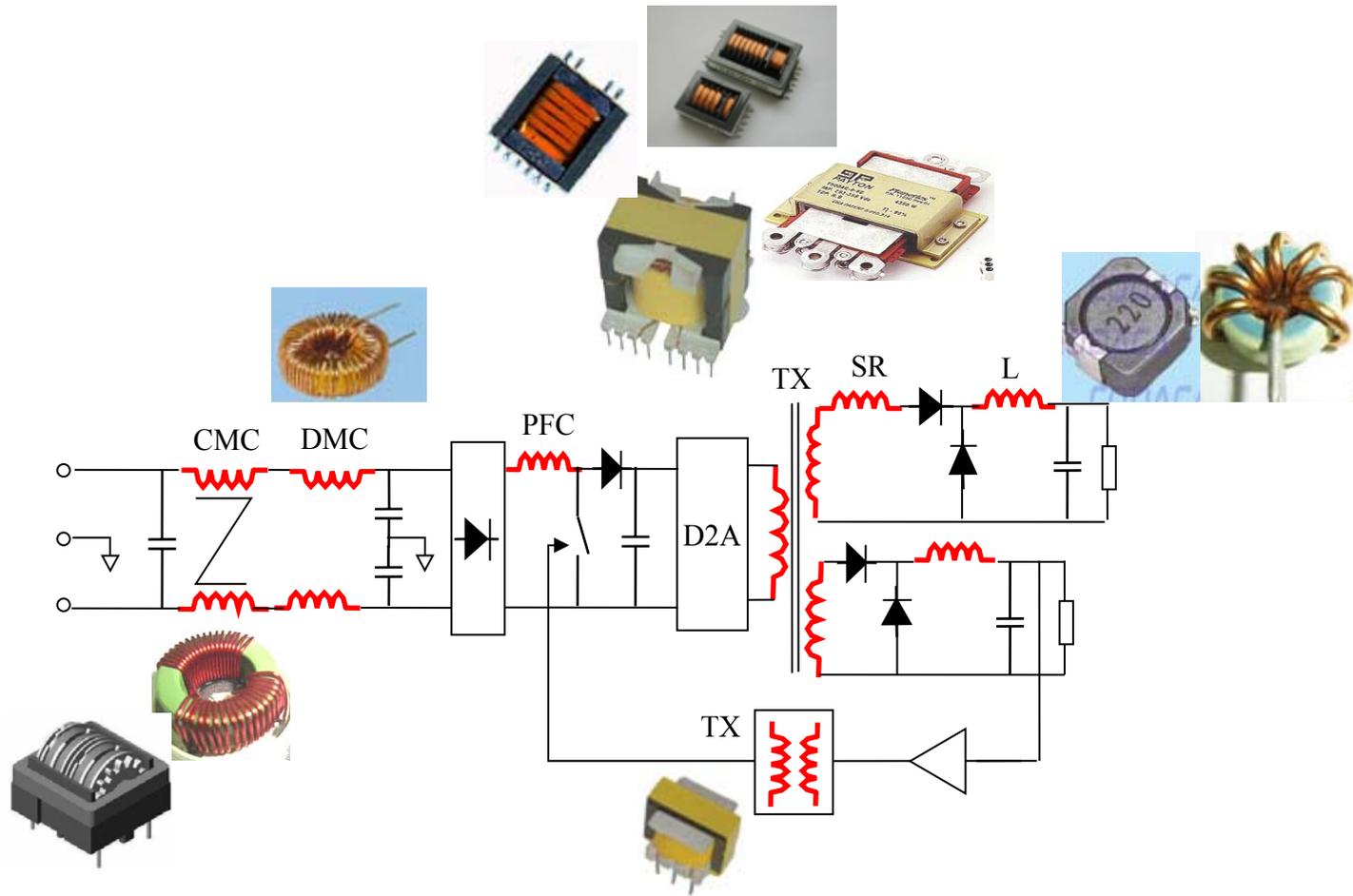


## 电感失效

# 铁粉芯的老化机理



# 高频磁元件与磁性材料考虑



$P_{cv}$

$B_s$

$B_r$

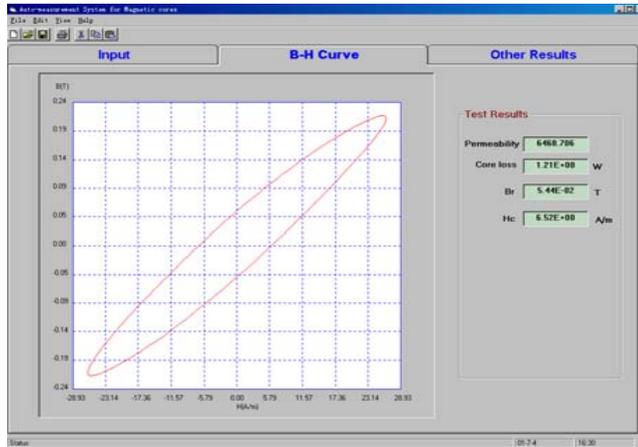
$\mu_i(f)$

$\mu_{\Delta}(I_d$

$\mu_a(B)$

c)

# 高频磁芯损耗的测量-交流I\*V法

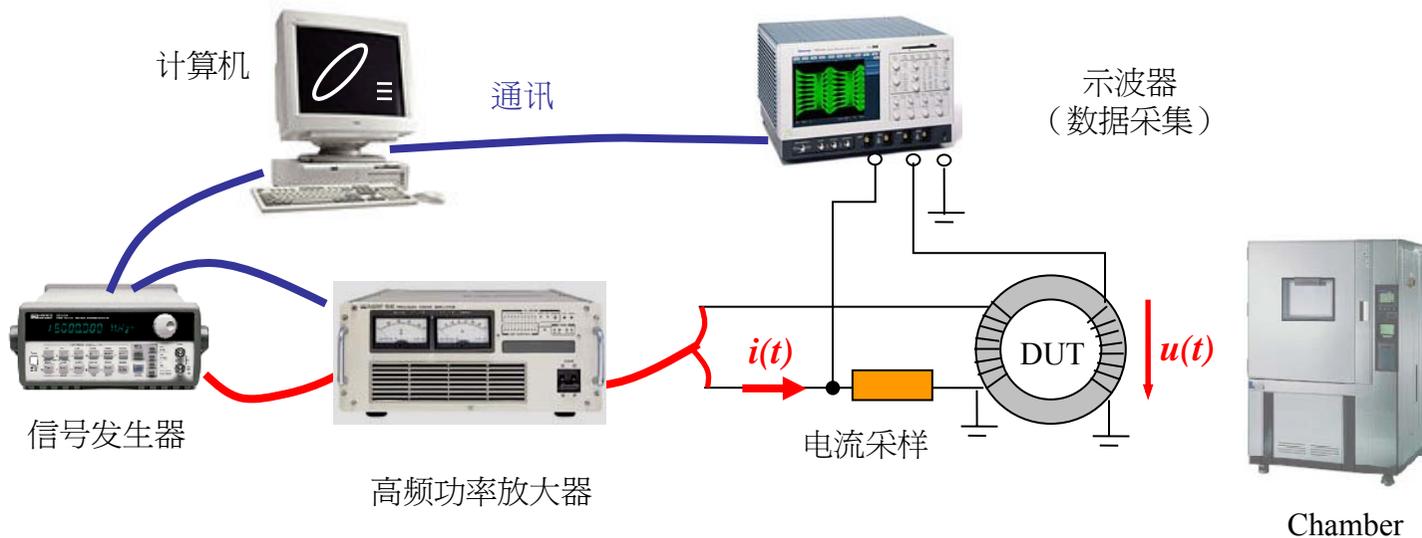


$$H(t) = \frac{i(t) \cdot N}{l_e} = K_H \cdot i(t)$$

$$B(t) = \frac{1}{N \cdot A_e} \int_{t_0}^{t_0+T} u(t) dt = K_B \cdot \int_{t_0}^{t_0+T} u(t) dt$$

$$P_{core} = \frac{1}{T_S} \int_0^{T_S} u \cdot i \cdot dt = \frac{1}{T_S} \int_0^{T_S} (A_e \cdot N \cdot \frac{dB}{dt}) \cdot (\frac{H \cdot l_e}{N}) \cdot dt$$

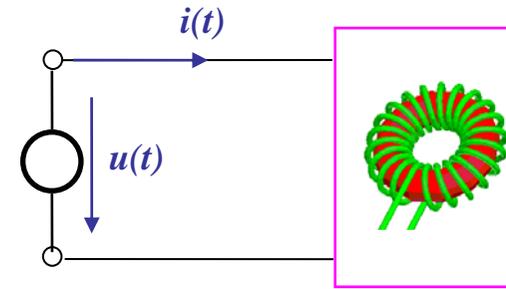
$$= A_e \cdot l_e \cdot \int_{B(0)}^{B(T_S)} H \cdot dB = V_e \cdot P_{cv}$$



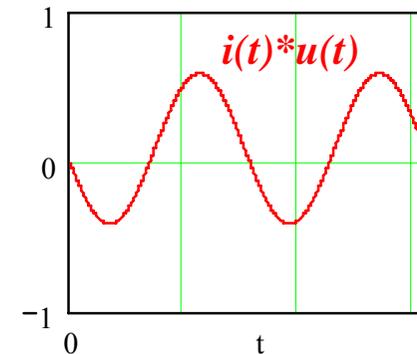
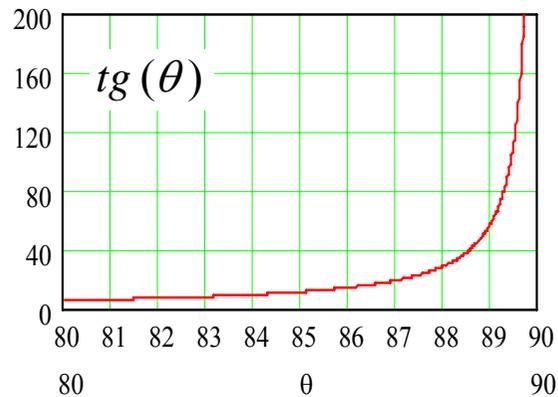
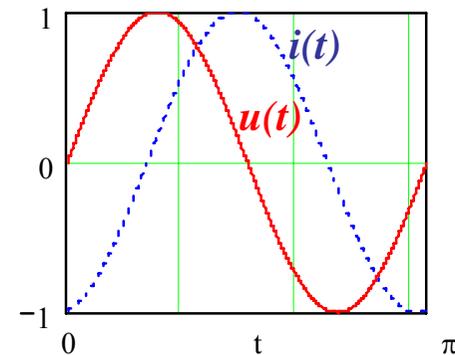
# 高频磁芯损耗测量的误差分析与困难

$$P = U \cdot I \cdot \cos \theta$$

$$\frac{\Delta P}{P} = \frac{\Delta U}{U} + \frac{\Delta I}{I} + \boxed{tg(\theta)\Delta\theta}$$



- High-frequency  $\rightarrow$  Large  $\Delta\theta = \Delta t * f$
- Large signal  $\rightarrow$  Large  $\Delta t$
- Low Loss  $\rightarrow$   $\theta$  approaches to  $90^\circ$

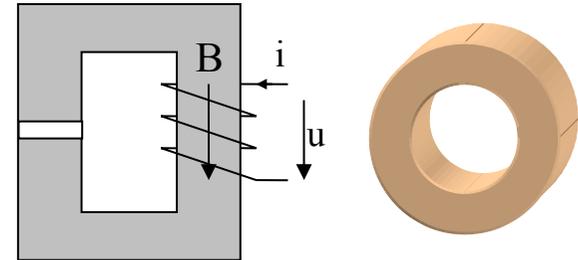
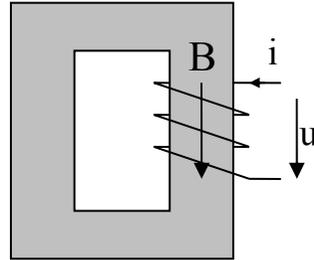


# 磁芯损耗测量 v.s. 气隙/磁粉芯

铁氧体高磁导率材料

有气隙铁氧体或低磁导率磁粉芯

$$\cos \theta = \frac{P}{U \cdot I}$$



□ U保持不变, B不变, P不变, 但由于电感大, I 很小, 所以  $\cos\theta$  较高, 误差较小。

□ U保持不变, B不变, P不变, 但由于电感降低, I 增大, 所以  $\cos\theta$  降低, 误差增大。

	Material	B (T)	f(kHz)	$\mu_r$	Pcv(kW/m <sup>3</sup> )	$\theta$ (°)
Powder	Magnetics HF60	0.1	50	60	400	88.9
	Magnetics XFlux60	0.1	50	60	600	88.4
	Magnetics KM60	0.1	50	60	360	89.0
	Magnetics MPP60	0.1	50	60	150	89.6
Ferrite	Ferroxcube 3C96	0.2	100	5500	300	80.6
	Ferroxcube 3C96	0.1	100	5500	40	85.0

# 软磁磁芯材料概述

## ❖ 粉芯磁材料(粉材)

Fe (铁粉芯)

MPP (高通铁镍合金)

High Flux (高通铁硅铝合金)

Kool Mu (铁镍铝合金)

Fe-Si (铁硅合金)



## ❖ 铁氧体磁材料(块材)

Mn-Zn

Ni-Zn

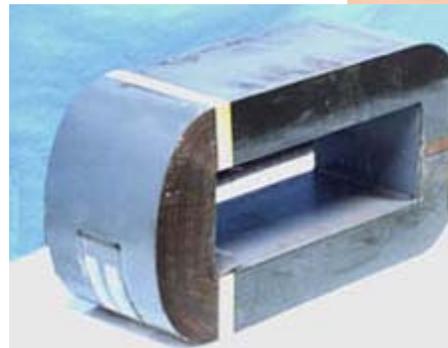


## ❖ 非晶磁材料(带材)

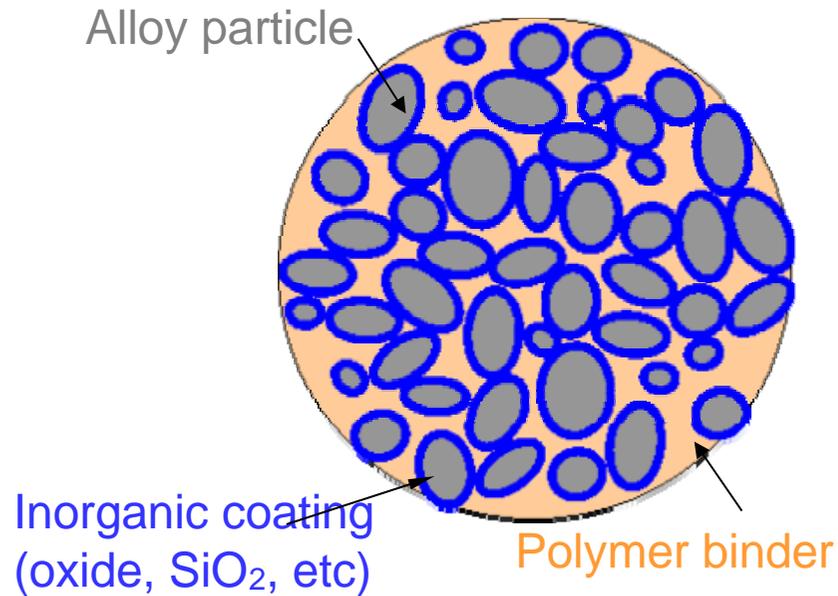
Silicon steel (硅钢片)

Permalloy (坡膜合金)

Amorphous (非晶)



# 粉芯磁材料的结构



Flux uneven → higher core loss

Min. polymer needed for forming → Lower  $\mu$

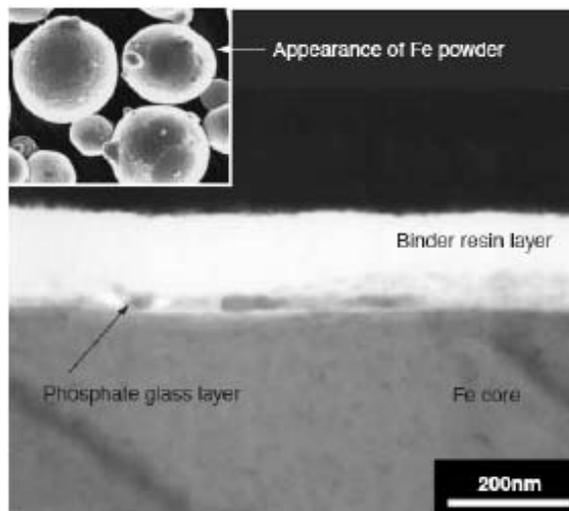
Powder conglutination → more eddy current

Polymer → Lower max. temperature (140-170°C)

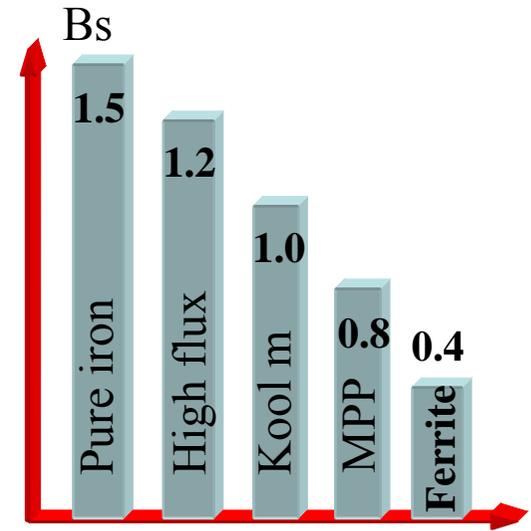
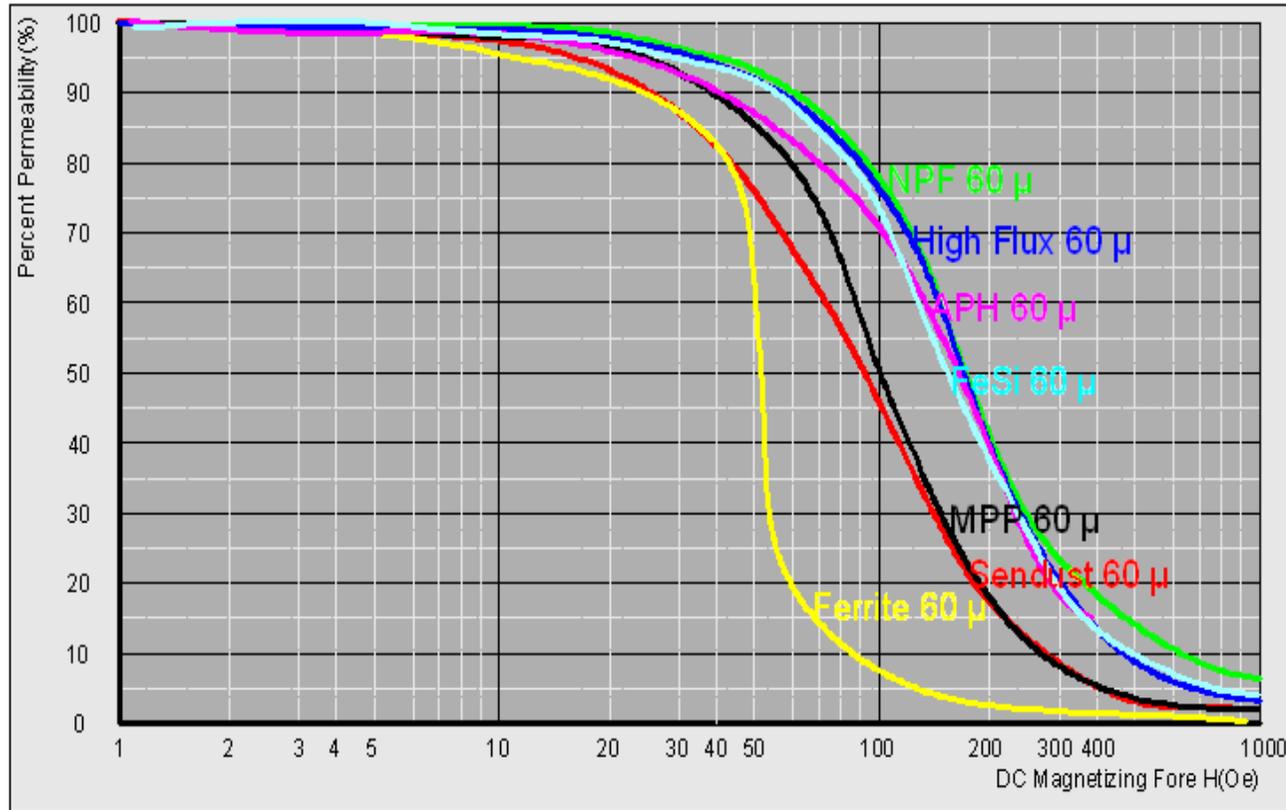
Force stress → Poor  $\mu$  consistency (>10%)

Distributed air-gap → Lower winding losses

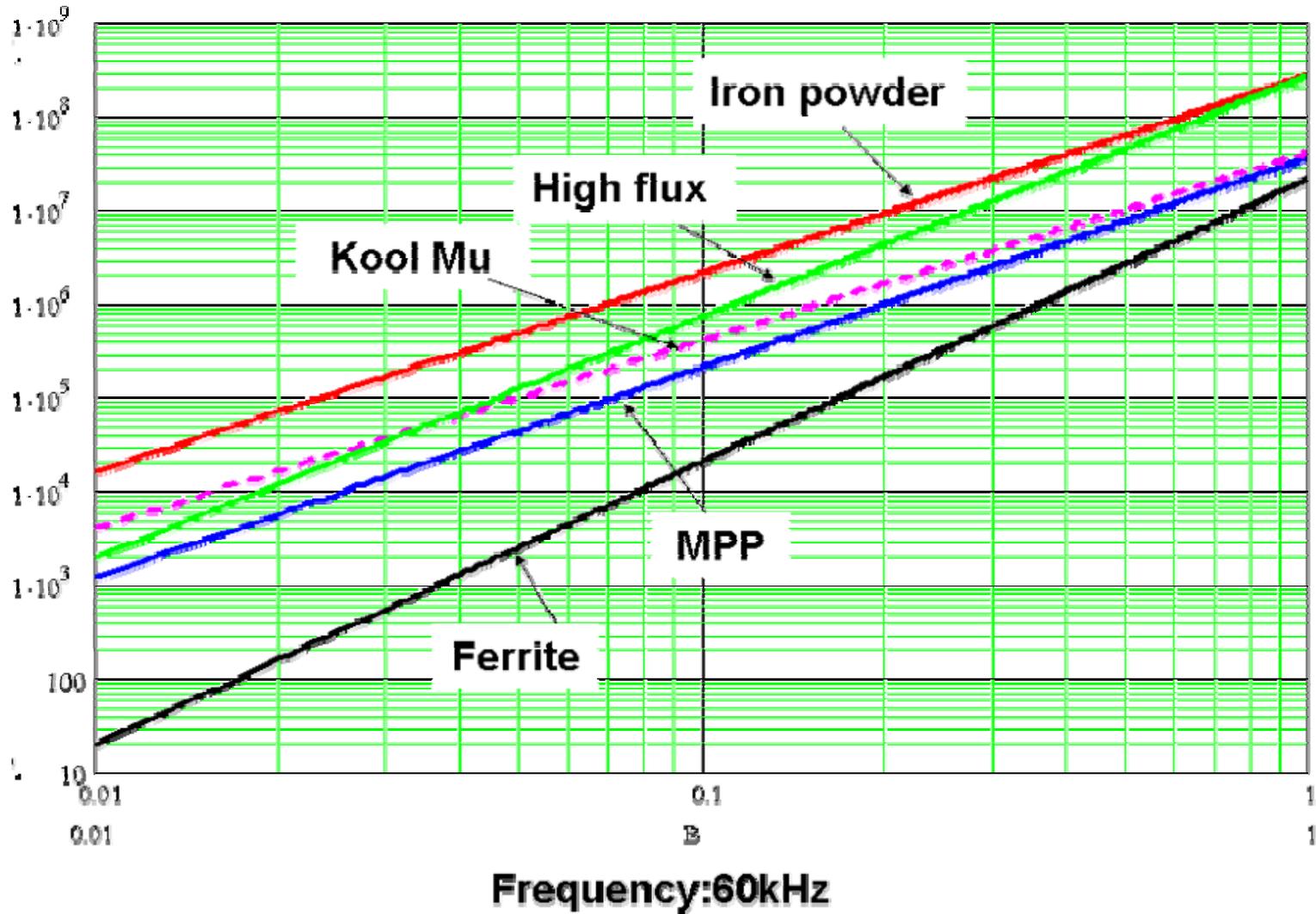
Distributed air-gap → Larger H<sub>dc</sub>



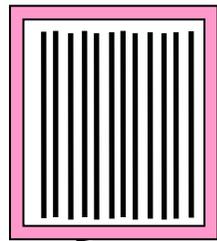
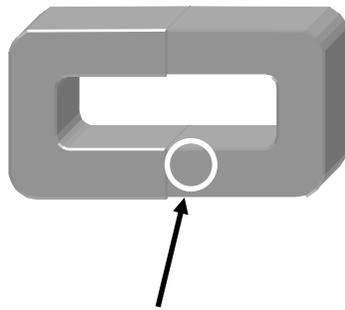
# 粉芯磁材料的饱和特性比较



# 粉芯磁材料的损耗特性比较



# 非晶带材磁材料



保护层

Thin thickness (0.5-15 mils) → Lower eddy current losses

Crispy → Difficult in making and winding

Annealing needed to reduce stress by tape winding  
→ Very poor  $\mu$  consistency (>20-200%)

High permeability

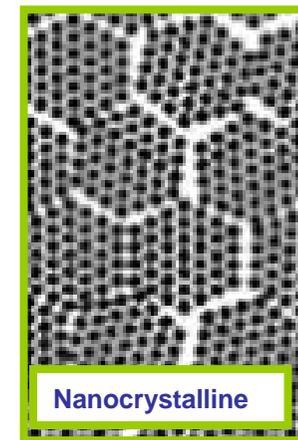
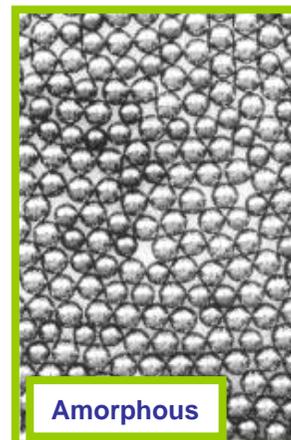
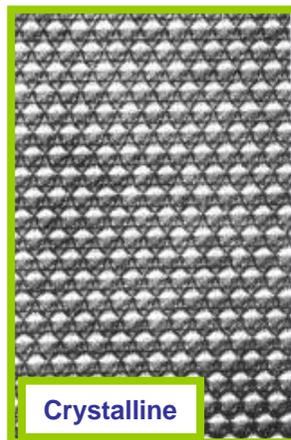
High saturation level (0.6-1.5T)

Tape materials: Permalloy (玻莫合金 80%Ni+20%Fe)

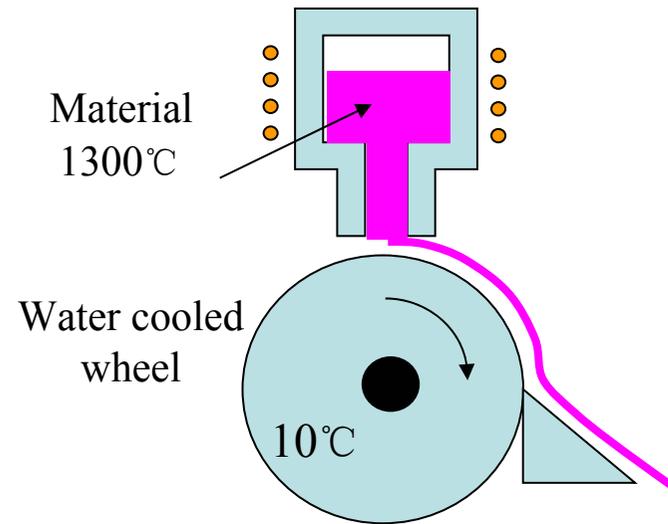
Amorphous: 非晶

-- 铁基(1.4-1.7T), 钴基(Bs:0.6-0.8T)

Fe-based nanocrystalline: 纳米晶



# 非晶帶材磁材的基本制程



Cooling speed: 1M Kelvin/S  
Speed: 100Km/h  
Thickness: 17-25 $\mu$ m

# 铁氧体磁材料

是由 $\text{Fe}_2\text{O}_3$ 和其他二价的金属氧化物(如 $\text{NiO}$ ,  $\text{ZnO}$ )等粉末混合烧结而成。具有高磁导率、高电阻率。适合于高频应用。

Mn-Zn Ferrite ( $\text{Fe}_2\text{O}_3 + \text{MnO} + \text{ZnO}$ ):

High-permeability, Lower resistivity, More eddy current loss

Ni-Zn Ferrite ( $\text{Fe}_2\text{O}_3 + \text{NiO} + \text{ZnO}$ ):

Low-permeability, Higher resistivity, More hysteretic loss





福州大学  
FUZHOU UNIVERSITY



**Thanks!**  
**Q & A**