KBTM

Magnet/coil design & effects

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Kibble Balance Technical Meeting
special session “knowledge transfer”
20 November 2025, BIPM

Outlines

1. Magnetic basics in KB experiments
2. A Brief history KB magnet-coil designs
3. How to design a KB magnet system
4. Evaluation performance of a KB magnet
5. Systematic effects and how to reduce
6. Summary & outlook

KB Magnetic basics: *Role of Bl in KBs*

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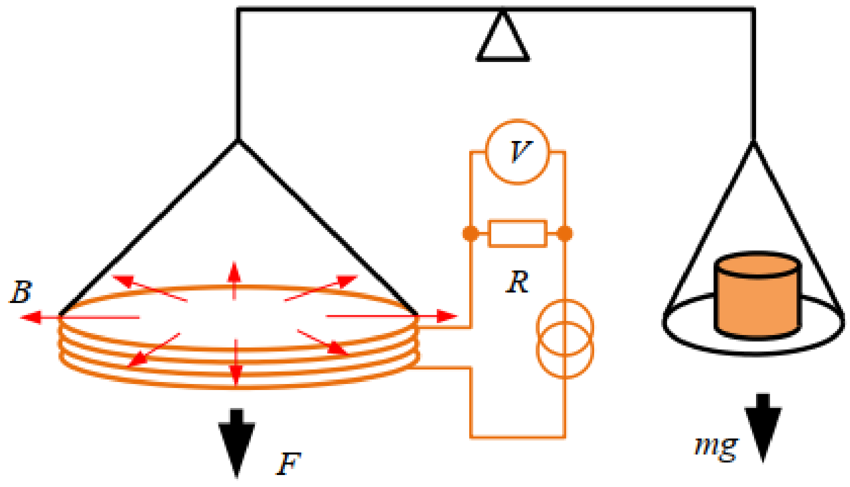
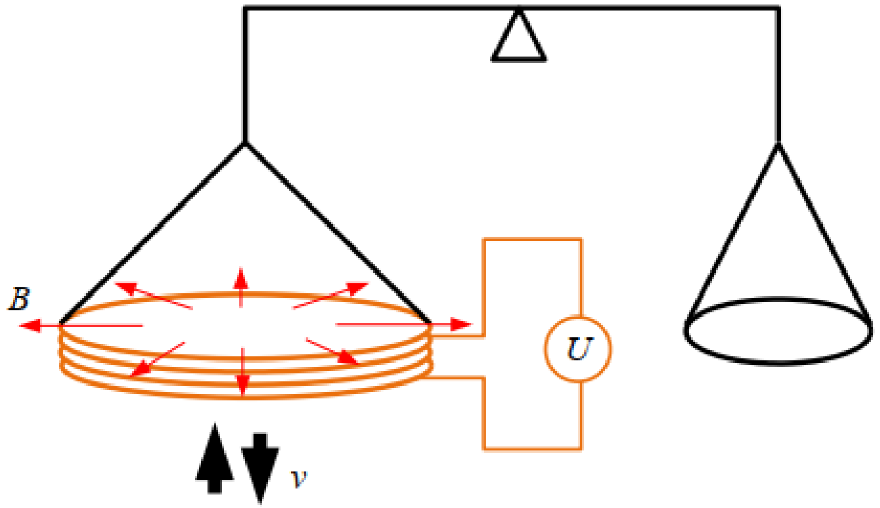


Weighing phase $mg = BlI$



$U = Blv$ Velocity phase

$$mgv = U\frac{V}{R}$$

$$m = \frac{UV}{gvR}$$

$$m = \frac{n_1 n_2 i f_1 f_2}{4gv} h$$

KB Magnetic basics: *A good Bl value helps*

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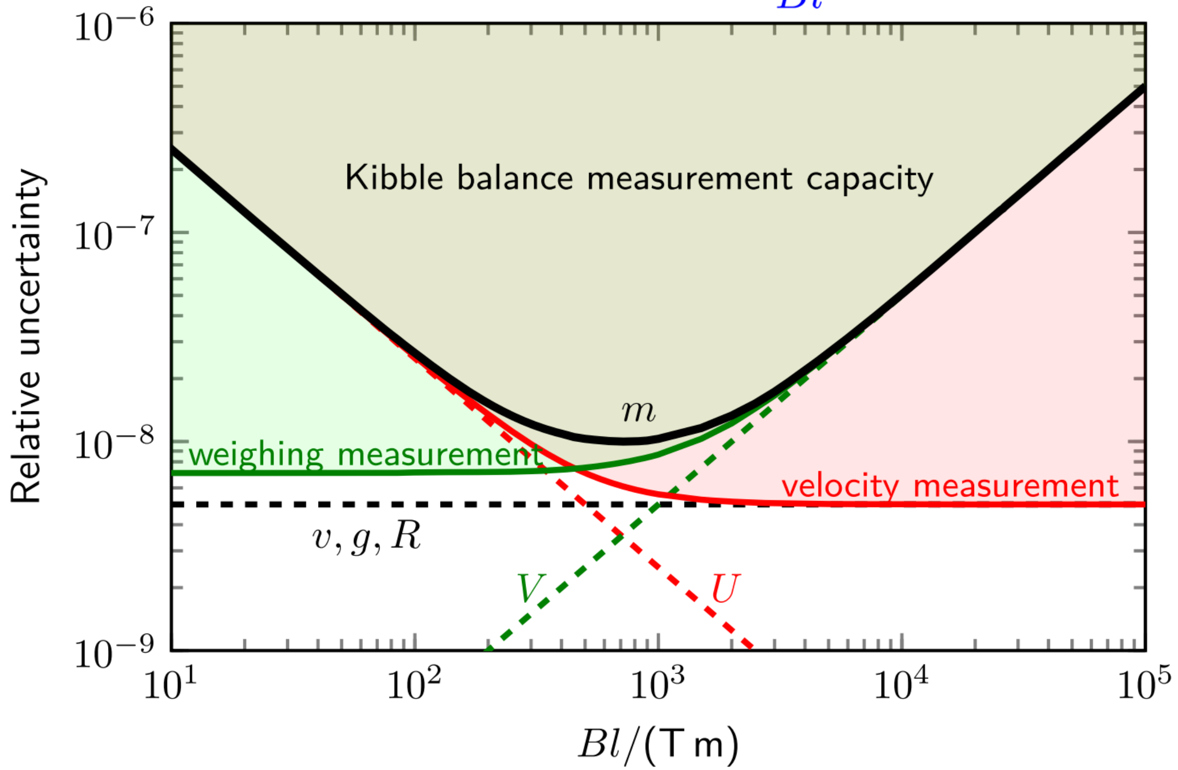
$$m = \frac{UV}{gvR} \Rightarrow \left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_v}{v}\right)^2 + \left(\frac{\sigma_g}{g}\right)^2 + \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{\sigma_U}{U}\right)^2 + \left(\frac{\sigma_V}{V}\right)^2$$

$mg = BlI$

$U = Blv \qquad V = \frac{mgR}{Bl}$

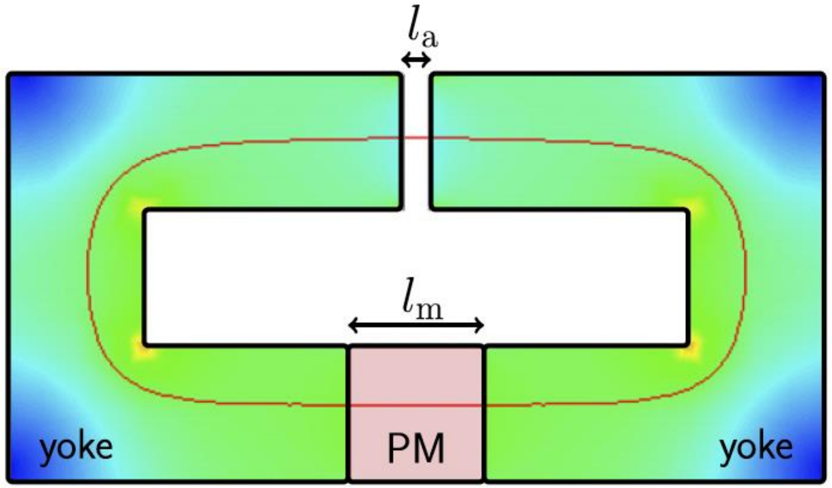
$$\left(\frac{\sigma_m}{m}\right)^2 = \left(\frac{\sigma_v}{v}\right)^2 + \left(\frac{\sigma_g}{g}\right)^2 + \left(\frac{\sigma_R}{R}\right)^2 + \left(\frac{1}{Bl}\right)^2\left(\frac{\sigma_U}{v}\right)^2 + (Bl)^2\left(\frac{\sigma_U}{mgR}\right)^2$$

$$(Bl)_{\mathrm{op}} = \sqrt{\frac{mgR}{v}}$$

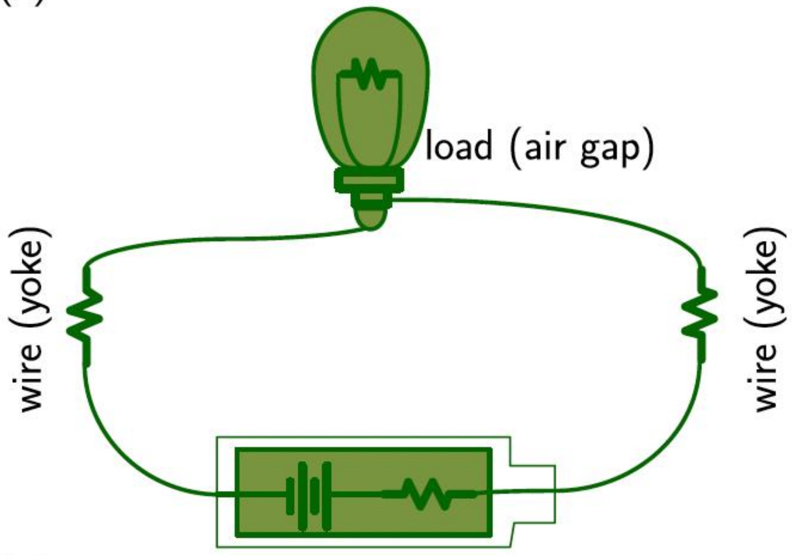


$\sigma_v/v = \sigma_g/g = \sigma_R/R = 5 \times 10^{-9}$, $\sigma_U = 5$ nV, $v = 2$ mm s^{-1}, $mgR = 1000\ \Omega$N.

KB Magnetic basics: *Magnetic Ohm's law*



(a)



(b) battery (PM)

$$I = U/R \qquad \Phi = \frac{\mathcal{F}}{\mathcal{R}}$$

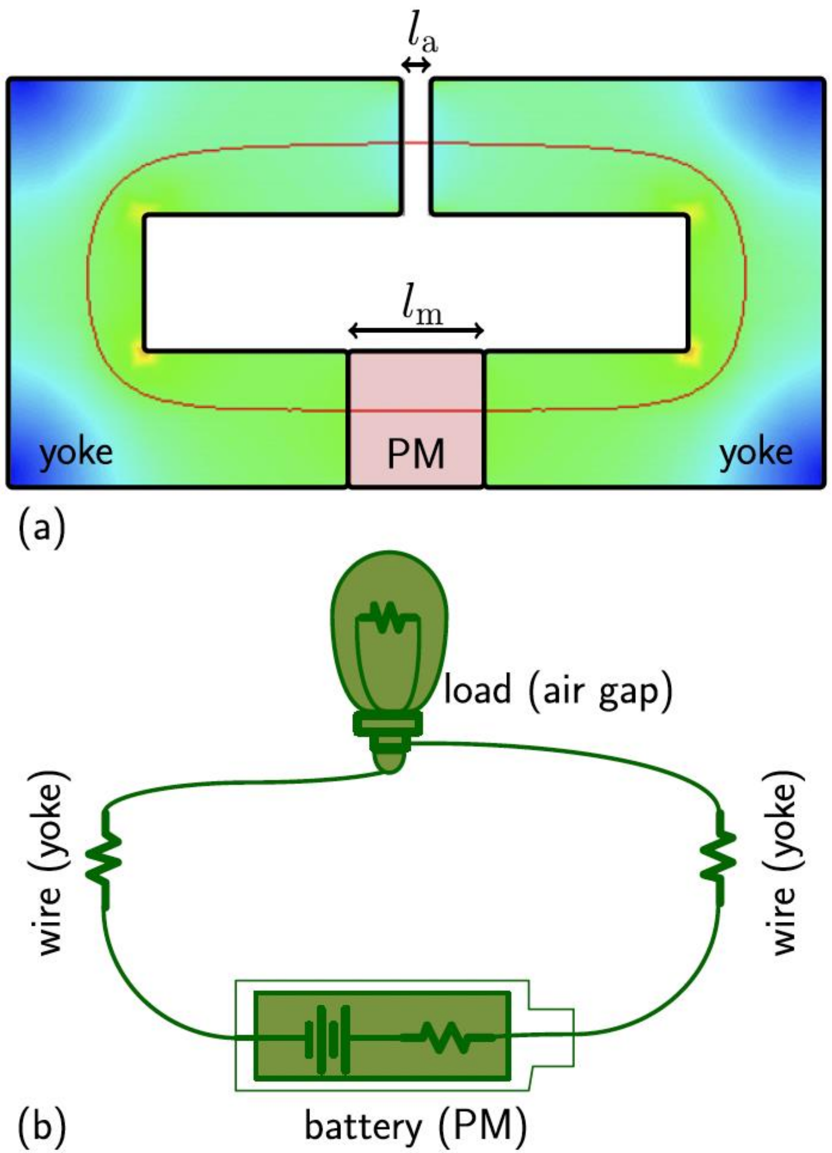
U the voltage electromotive force (EMF)
$\mathcal{F}$ the magnetomotive force (MMF).

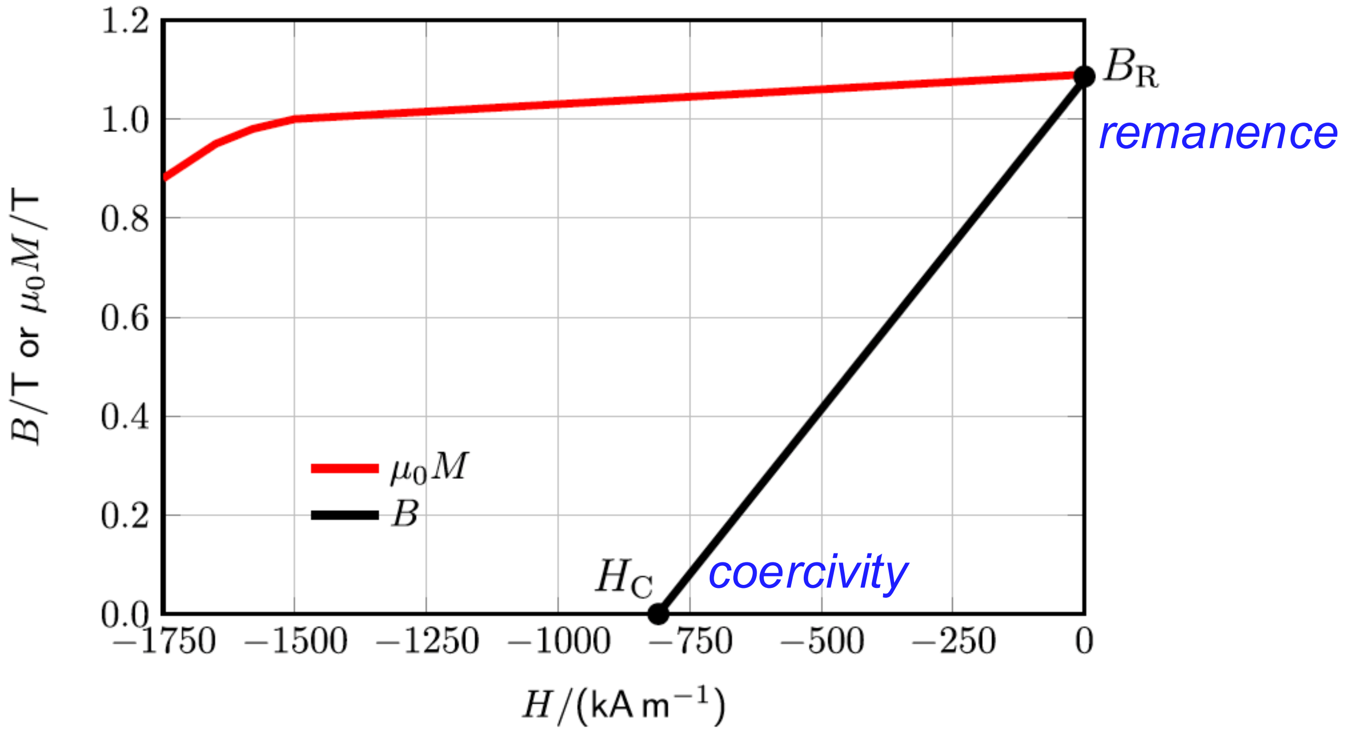
I the electrical current
Φ the magnetic flux

R the electrical resistance
$\mathcal{R}$ the magnetic reluctance

$$R_a = \frac{l_a}{S\mu_0}, \qquad R_y = \frac{l_y}{S\mu_0\mu_r}, \qquad R_m = \frac{l_m}{S\mu_0\mu_m},$$

KB Magnetic basics: *Magnetic Ohm‘s law*





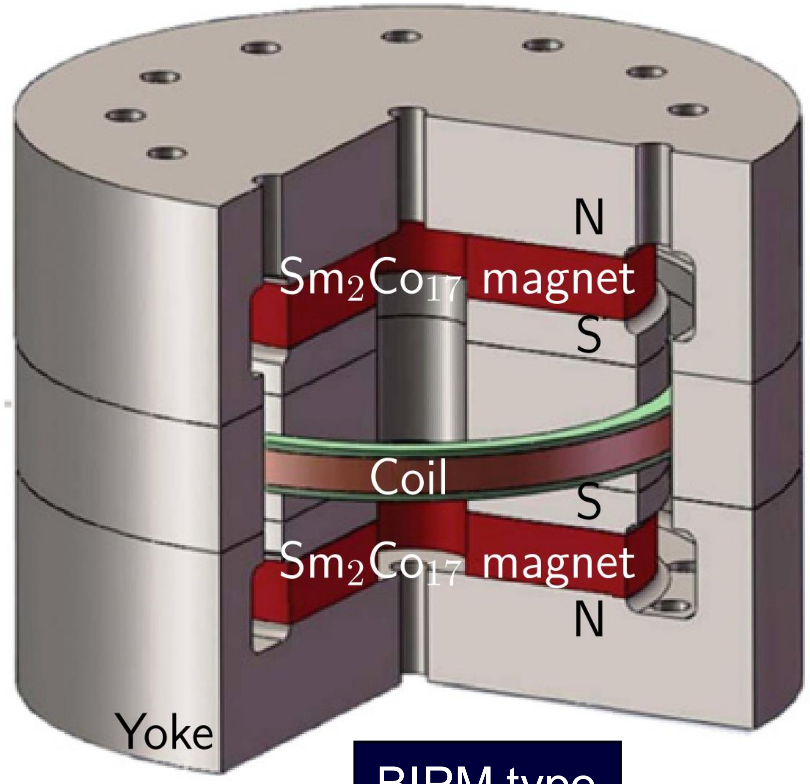
$$\Phi\left(\frac{l_m}{S\mu_m\mu_0}+\frac{l_y}{S\mu_0\mu_r}+\frac{l_a}{S\mu_0}\right)=\frac{B_R}{\mu_m\mu_0}l_m=-H_C l_m$$

Double the PM width, the field will not be doubled!

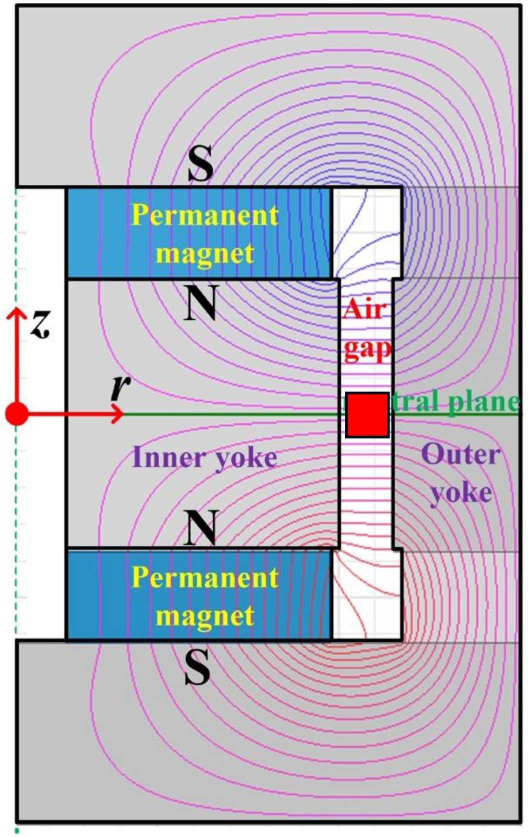
Li S, Schlamminger S 2022 Metrologia 59 022001 (30pp)

KB Magnetic basics: *What is Bl ?*

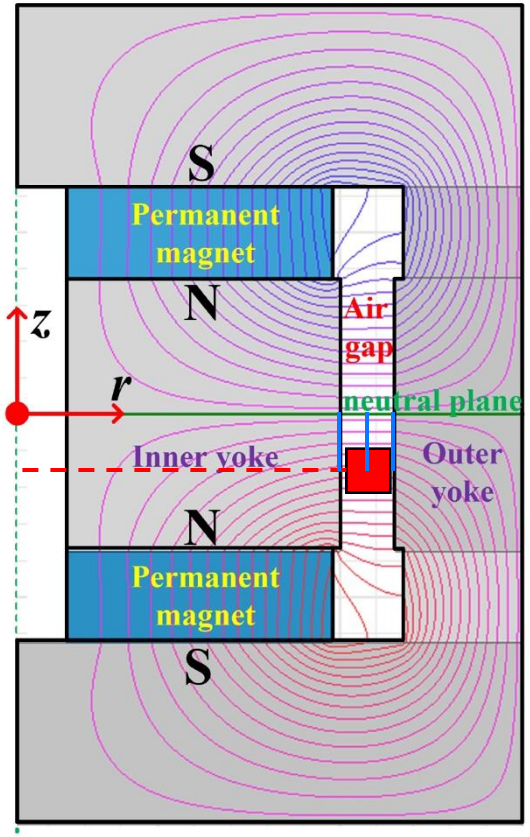
$$Bl = \frac{\partial \Phi}{\partial z} = \int (\mathbf{dl} \times \mathbf{B})_z \qquad Bl : [\mathrm{Tm}] = \frac{[\mathrm{Tm}^2]}{[\mathrm{m}]} : \frac{\partial \Phi}{\partial z}$$



BIPM type

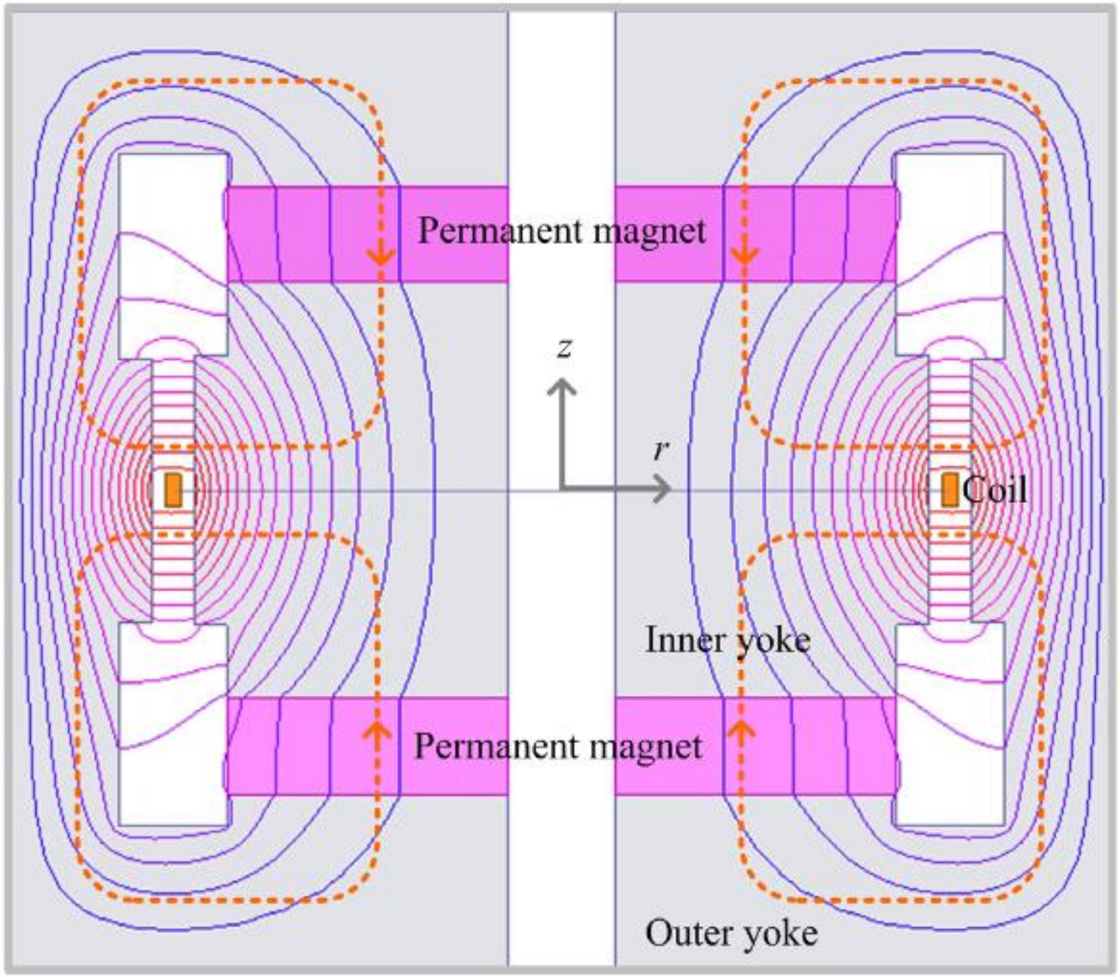


$z = 0, \Phi = 0$



$\Phi(z) = Blz$

KB Magnetic basics: *The virtual principle*



*Magnetic Energy=flux linkage*current*

The energy of a bifilar coil system is

$$E = \frac{L}{2} I_1^2 + \frac{L}{2} I_2^2 + M I_1 I_2$$

By the virtual principle , the force is

$$\Delta F = \frac{\partial E}{\partial z} = \frac{I^2}{2} \frac{\partial L}{\partial z}$$

Note that a current constant system,
the sign should be positive!
The current offers additional energy (2E)

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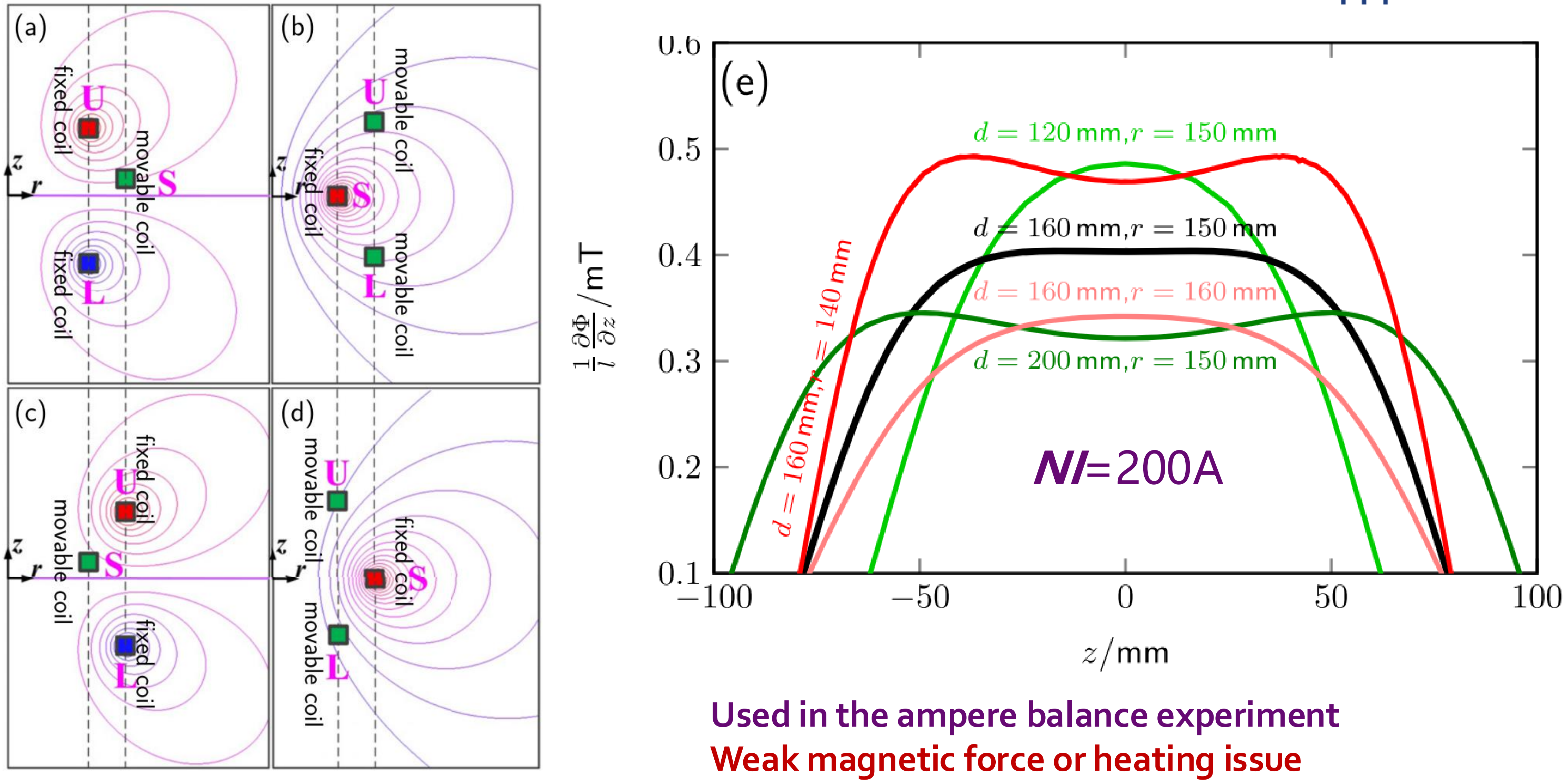
KB magnet-coil history: *conventional coil system*

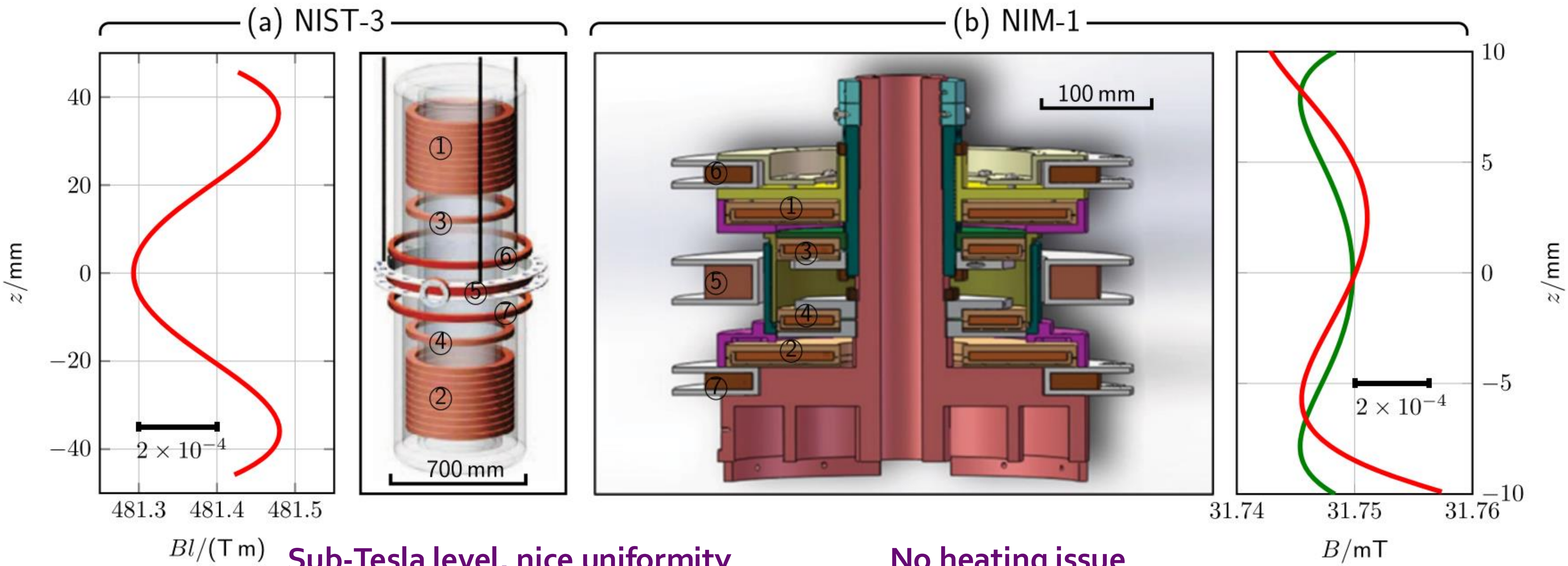


Used in the ampere balance experiment

Weak magnetic force or heating issue

Li S, Schlamminger S 2022 Metrologia 59 022001 (30pp)

KB magnet-coil history: *multi-coil magnet system*



Sub-Tesla level, nice uniformity

High operational cost

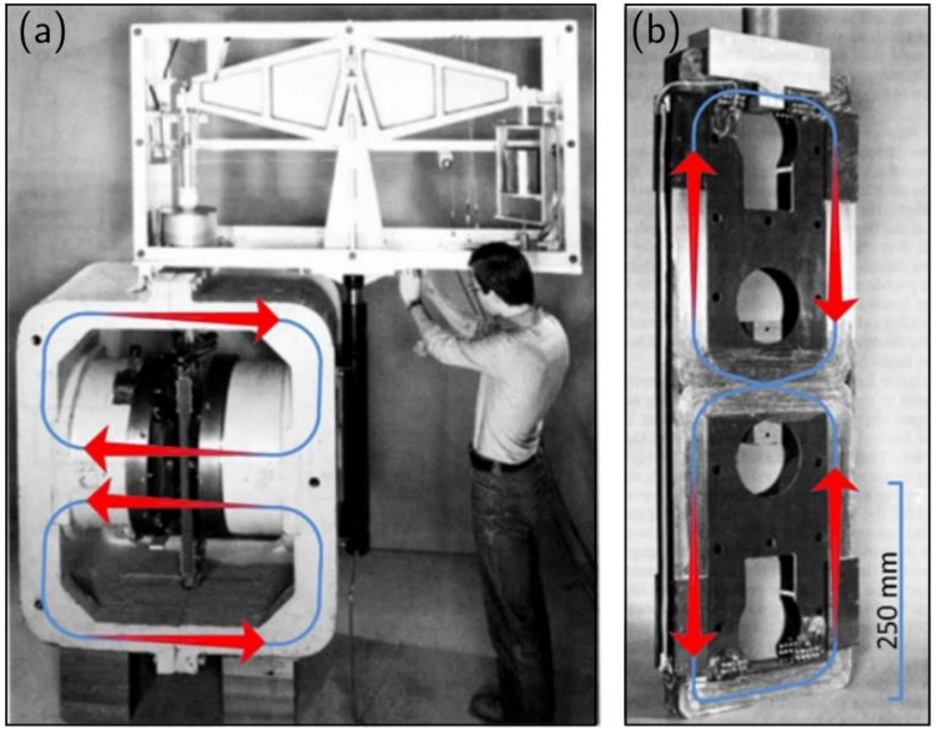
Steiner R et al J. Res. Natl Inst. Stand. Technol. 110 1–26

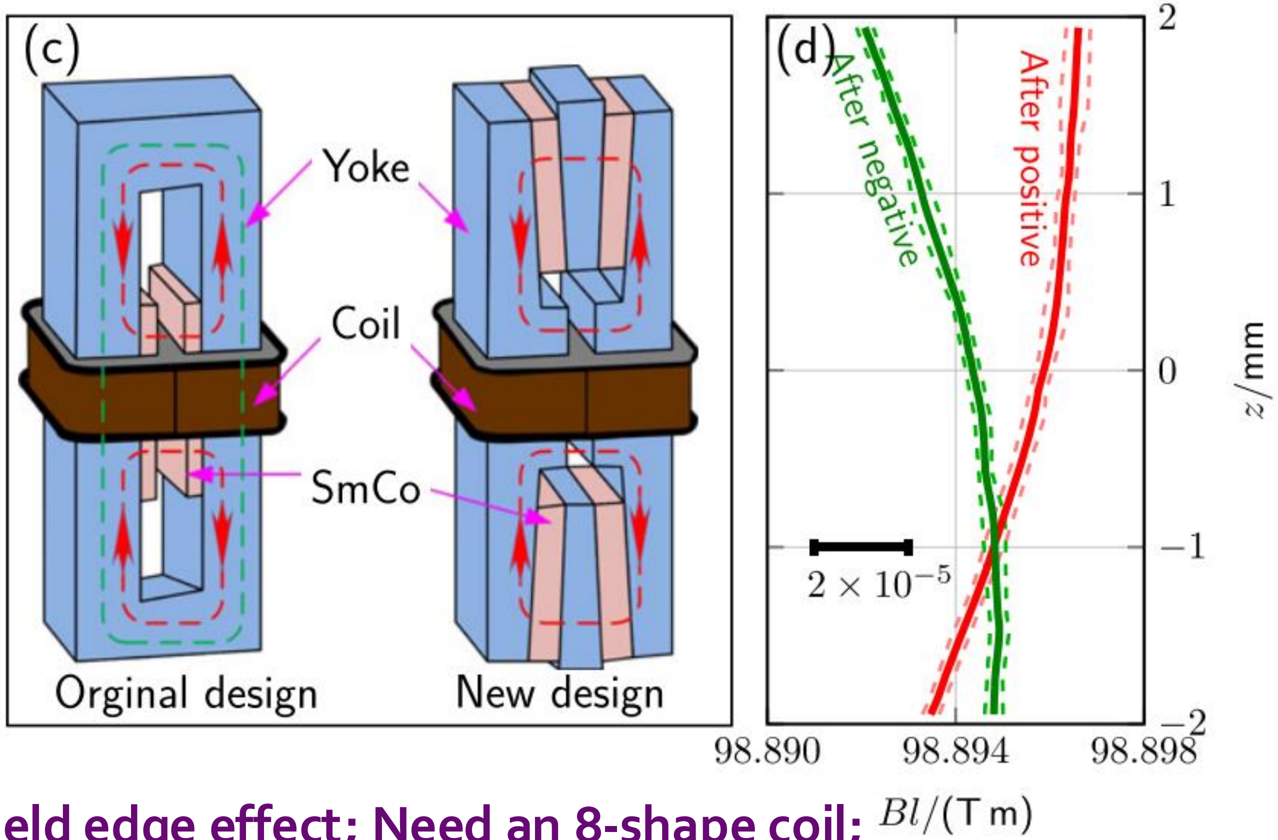
No heating issue

Weak field, field uniformity

Xu J et al 2016 Metrologia 53 86–97

KB magnet-coil history: *Flat PM system*





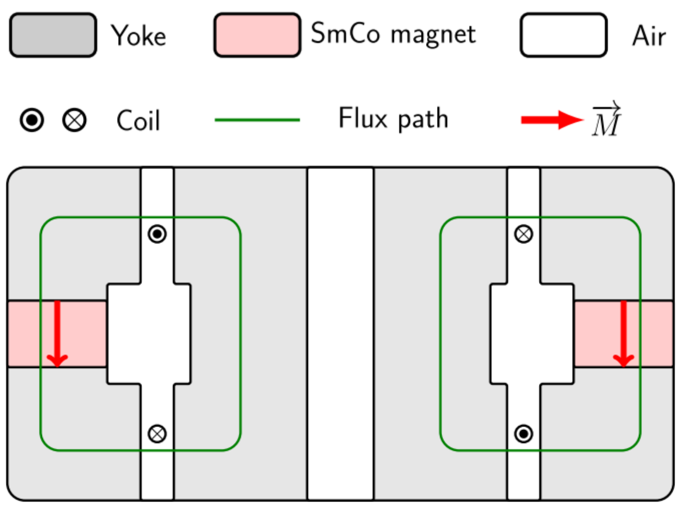
56 mm width, 0.3 m × 0.3 m sectional area air gap.
0.68 T in the air gap center.
The magnet weighs 6000 kg, and the coil 30 kg.

Field edge effect; Need an 8-shape coil;
Large size or low efficiency compared to radial system;
Be careful with closed yoke path!

Kibble B P et al 1990 Metrologia 27 173–92

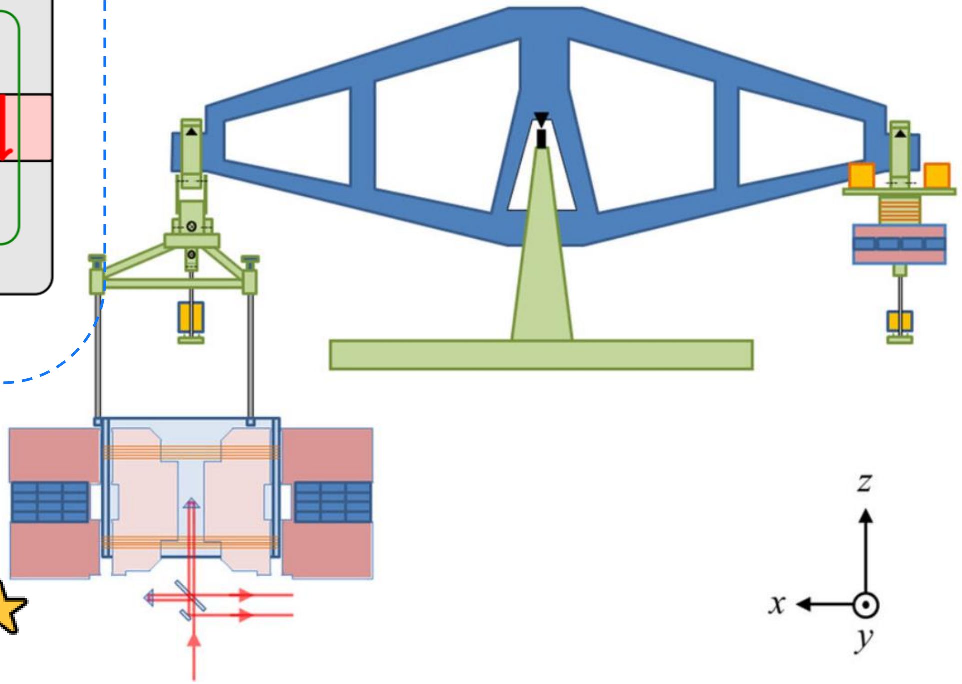
Eichenberger A et al 2011 Metrologia 48 133–41
Beer W et al 2003 IEEE TIM 52 626–30

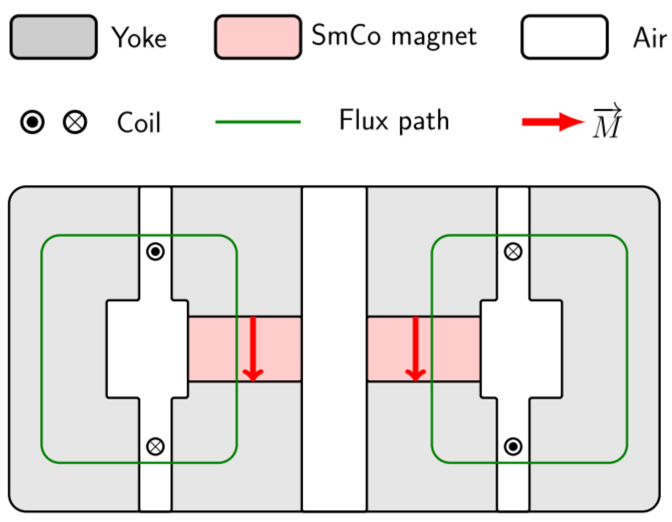
KB magnet-coil history: *Radial PM system*



(a) NPL-II type

Great merit: nice cancellation of electromagnetic noise!





(b) NPL-NG type

First radial PM system

Symmetry: ★★★★★

Efficiency: ★★★★

Shielding: ★★★

NPL's next generation KB magnet

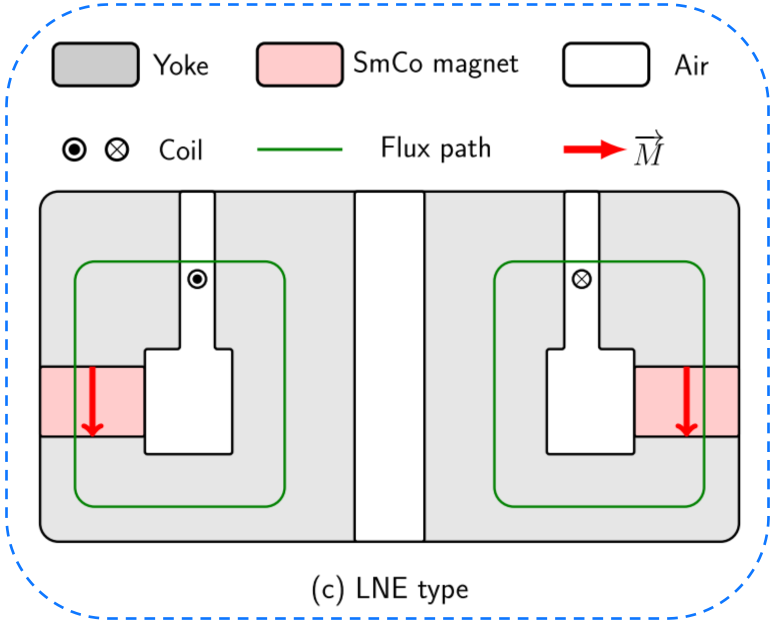
Symmetry: ★★★★★

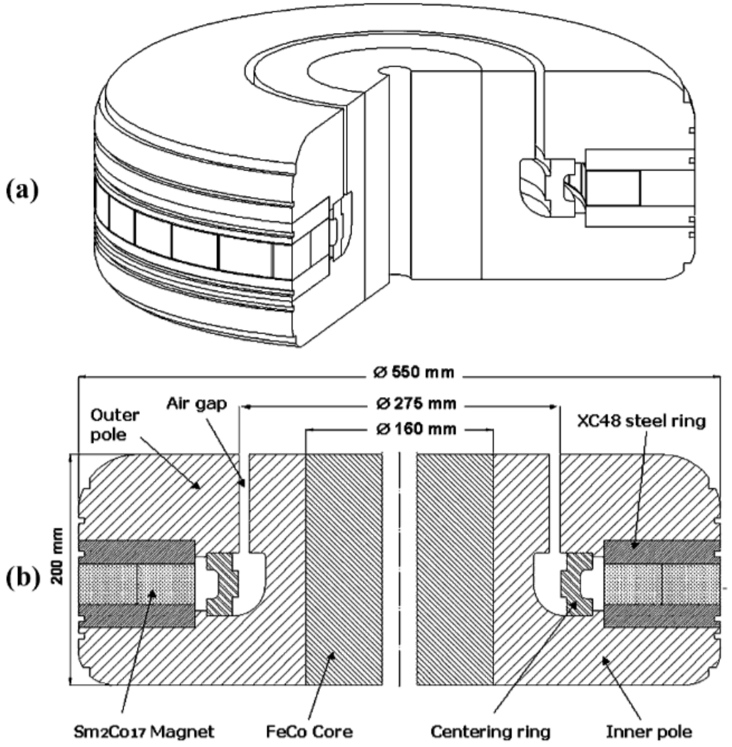
Efficiency: ★★★

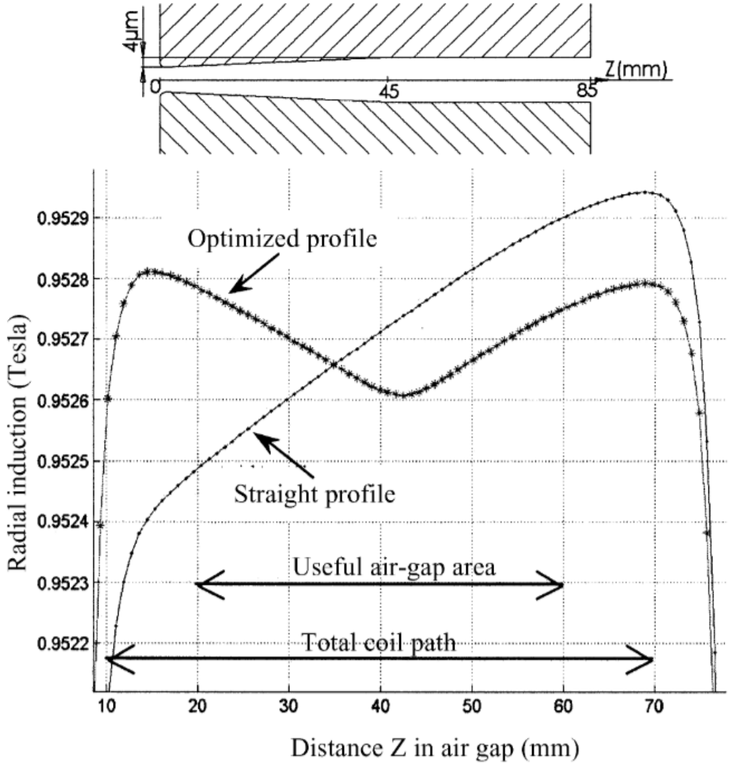
Shielding: ★★★★

Robinson I A 2009 IEEE TIM 58 936–41
Wood BM et al 2017 Metrologia 54 399–409
Robinson I A 2018 CPEM

KB magnet-coil history: *Radial PM system*







PM system with the strongest field

Symmetry: ★★★★

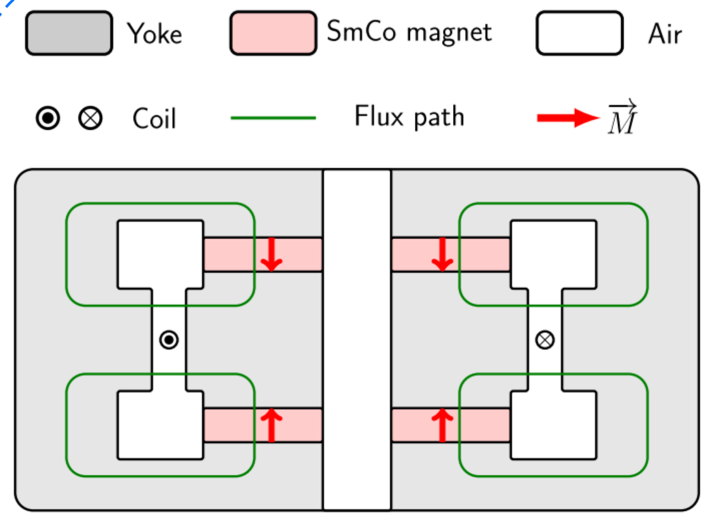
Efficiency: ★★★★

Shielding: ★★★

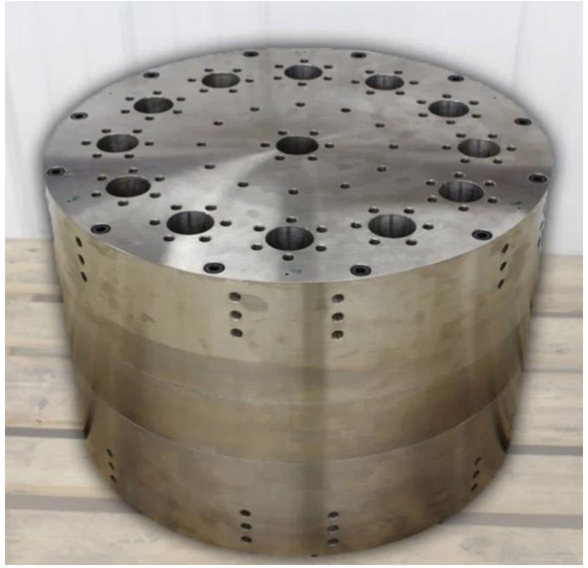
Gournay P et al 2005 IEEE TIM 54 742–5

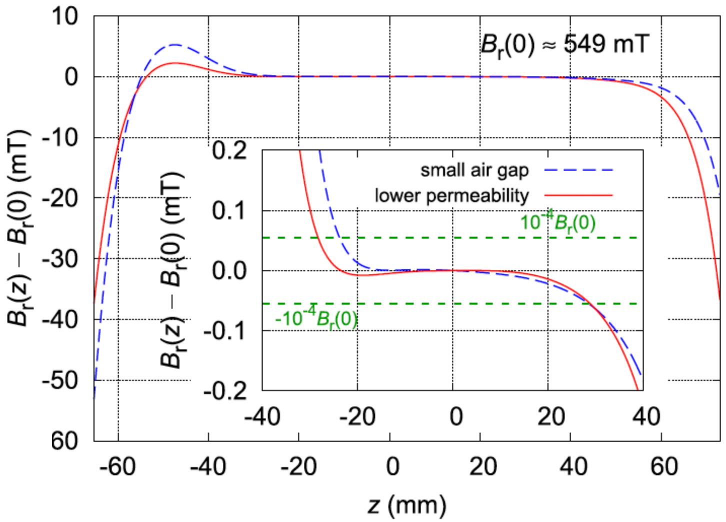
KB magnet-coil history: Radial PM system

BIPM



(d) BIPM type



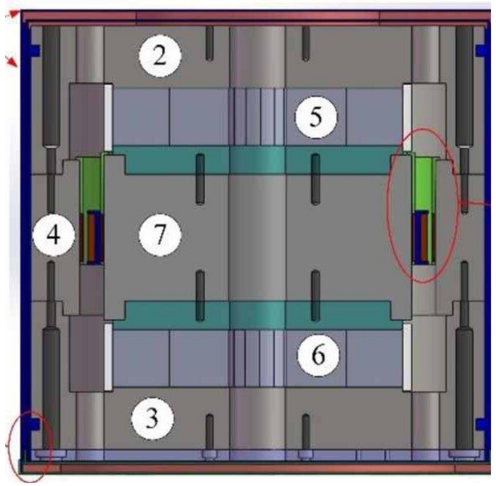


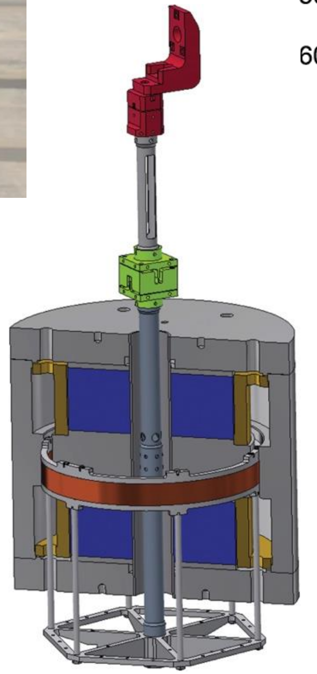
Most popular PM system

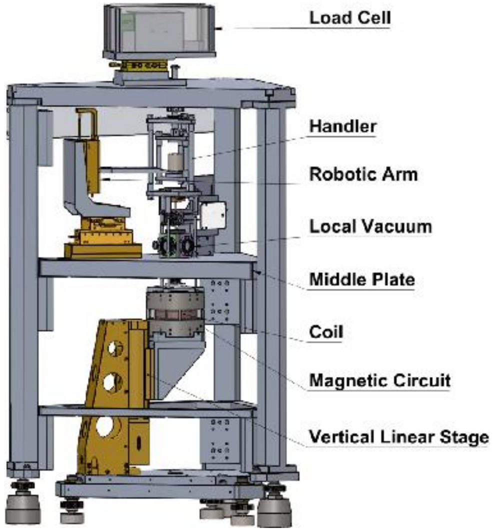
Symmetry: ★★★★★

Efficiency: ★★★★★

Shielding: ★★★★★



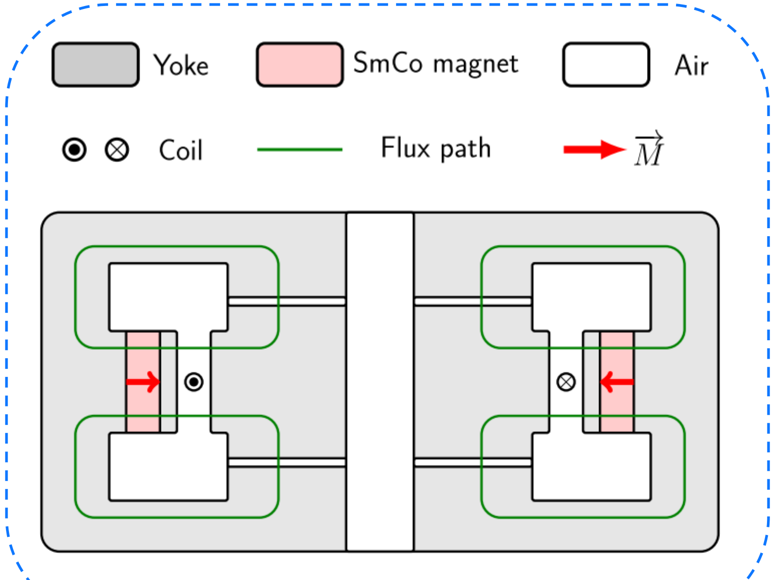




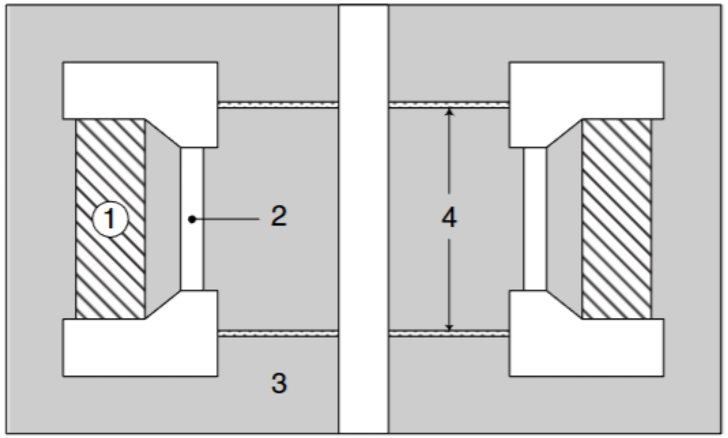
Seifert F et al 2014 IEEE TIM 63 3027

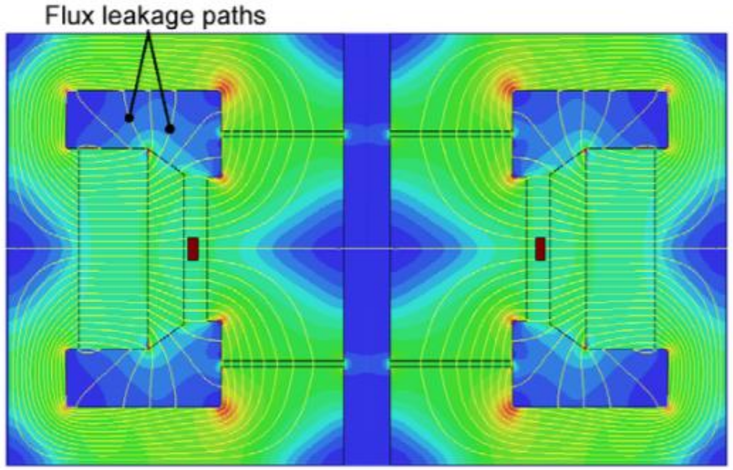
NIST-4, METAS-2, NIM, KRISS, UME, Tsinghua University, …

KB magnet-coil history: *Radial PM system*



(e) MSL type





Coil flux return, and additional air gap is required, which reduce the field strength at the coil position.

Installation may be not easy.

Symmetry: ★ ★ ★ ★ ★

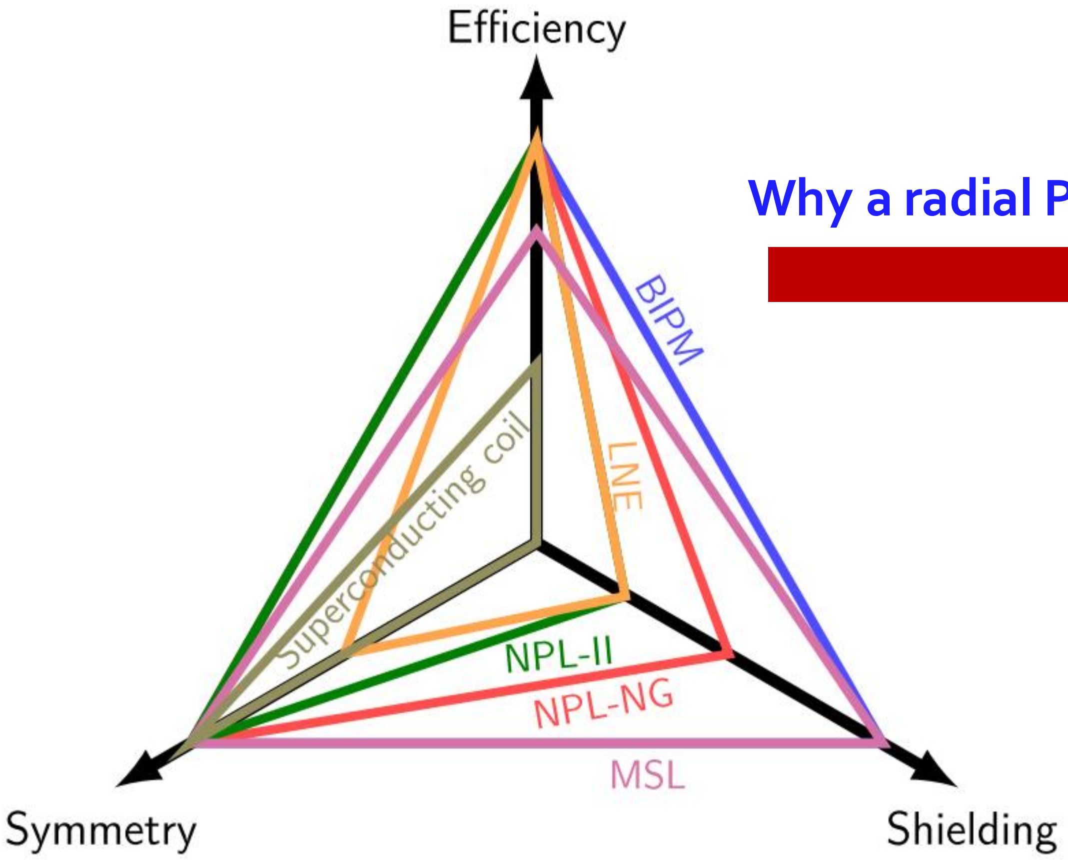
Efficiency: ★ ★ ★

Shielding: ★ ★ ★ ★ ★

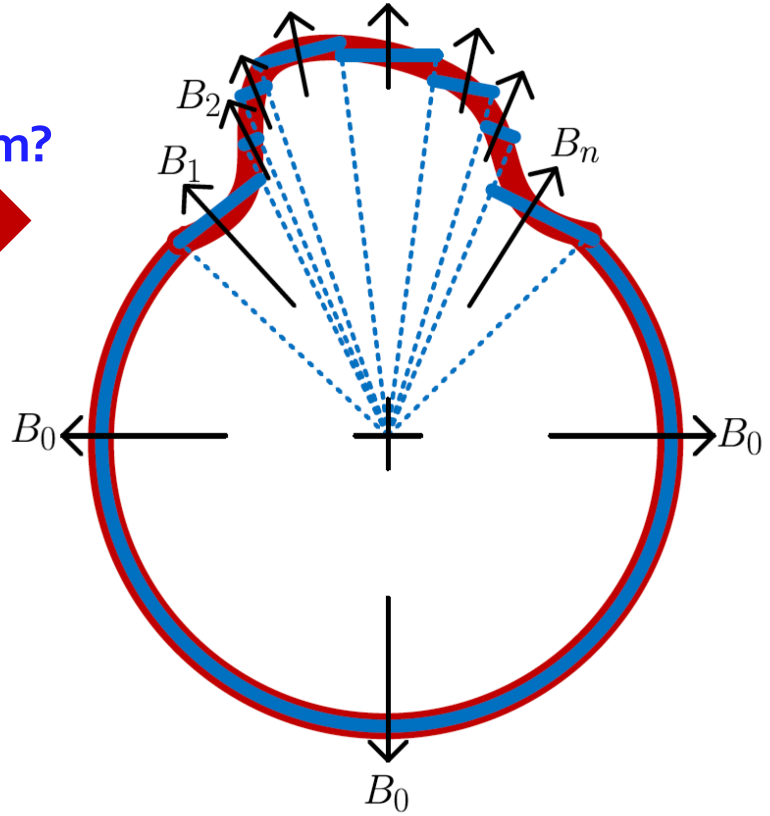
Sutton C M et al Metrologia 51 (2014) S101–S106

KB magnet-coil history: *Radial PM system*

BIPM



Why a radial PM system?



$$\vec{\nabla} \cdot \vec{B} = \frac{1}{r}\frac{\partial (rB_r)}{\partial r} + \frac{1}{r}\frac{\partial B_\varphi}{\partial \varphi} + \frac{\partial B_z}{\partial z} = 0$$

$$\frac{B_r}{r} + \frac{\partial B_r}{\partial r} = -\frac{\partial B_z}{\partial z}$$

Li S et al Metrologia 59 (2022) 022001 (30pp)

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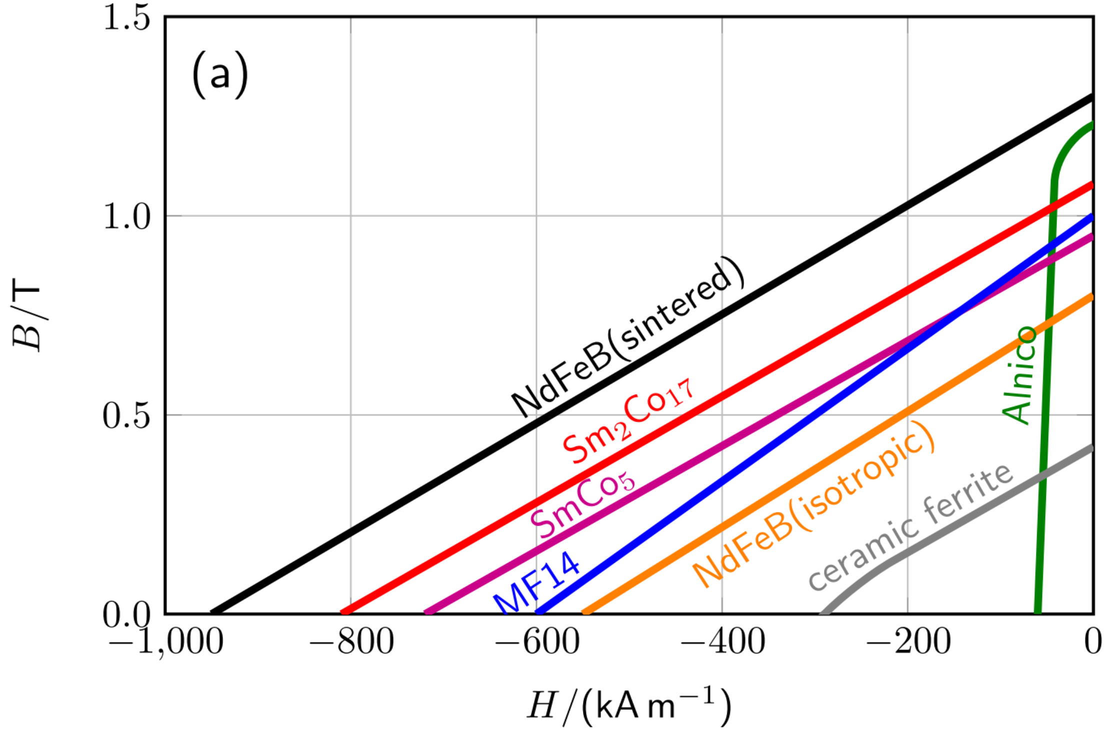
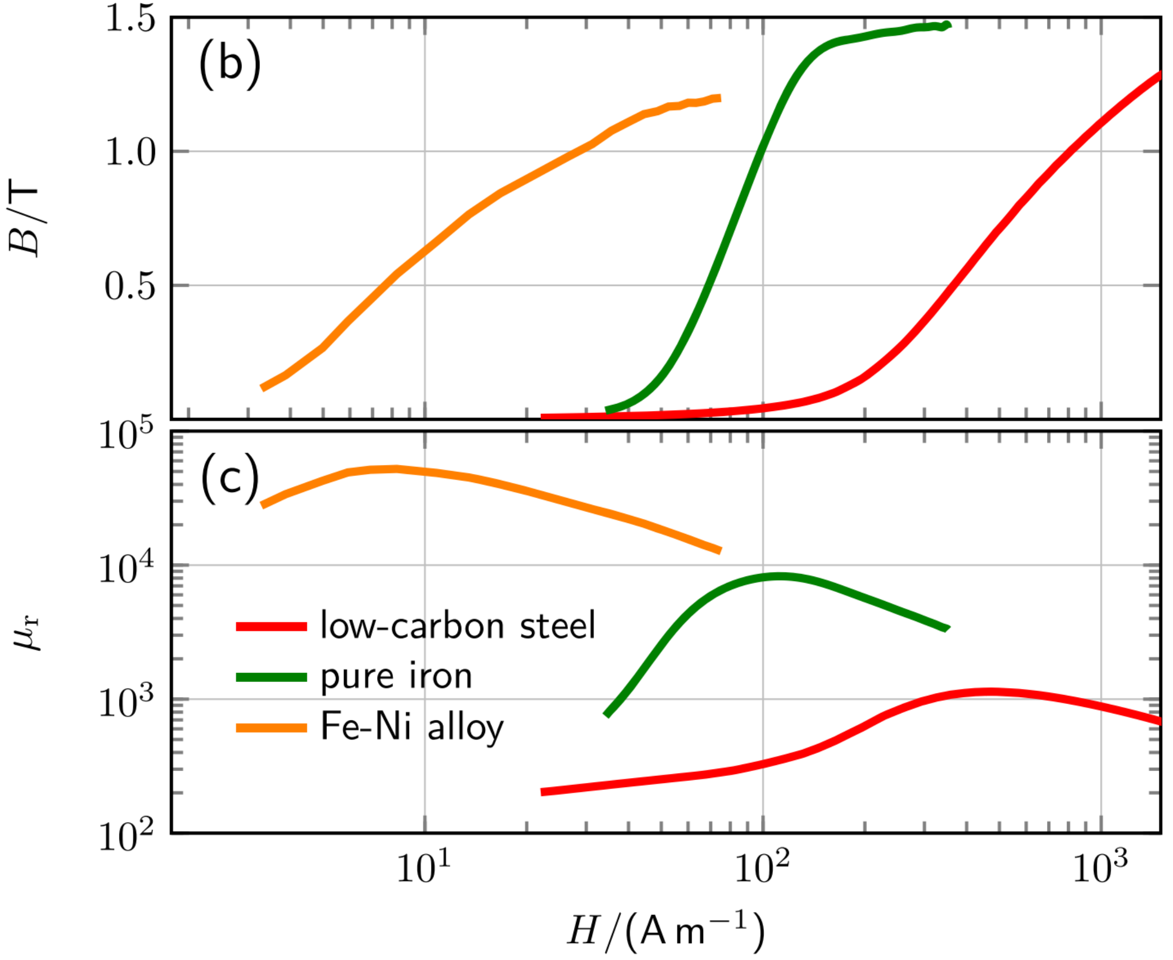
KB magnet design: *Magnetic materials*





NdFeB: high Hc, high Tc (-1000ppm/K)

Sm2Co17: Tc(-300ppm/K), lower Hc

(Gd,Sm)2Co17: low Tc, Hc is 20% less than Sm2Co17

Pure iron seems to be a good choice.

Li S, Schlamminger S 2022 Metrologia 59 022001 (30pp)

KB magnet design: Field strength at coil pos

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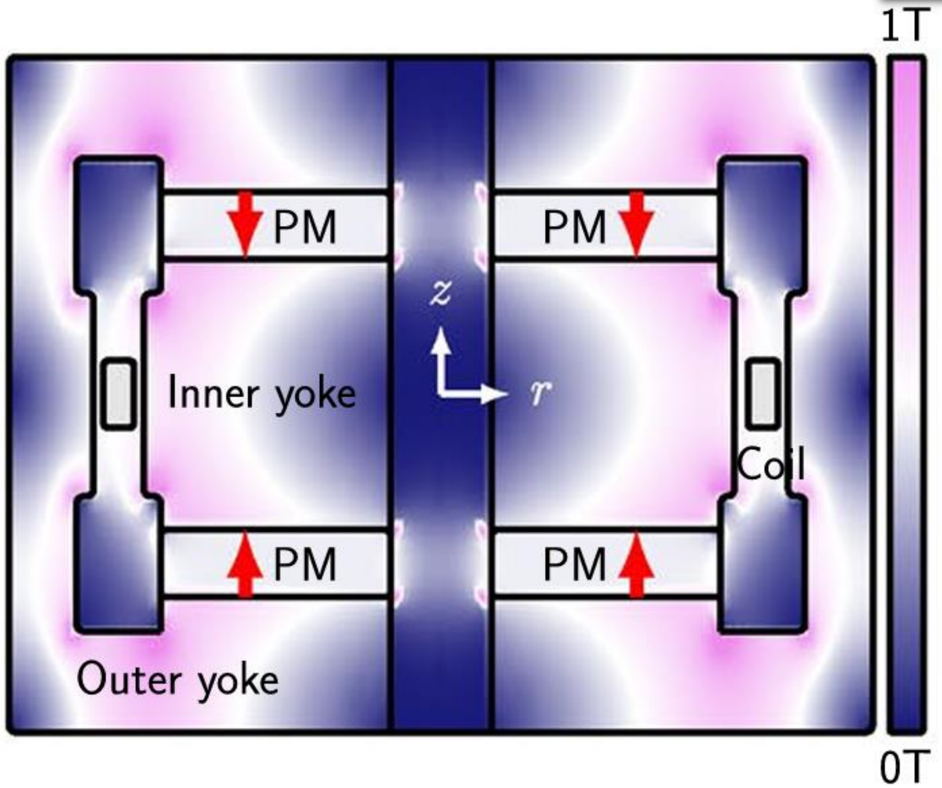
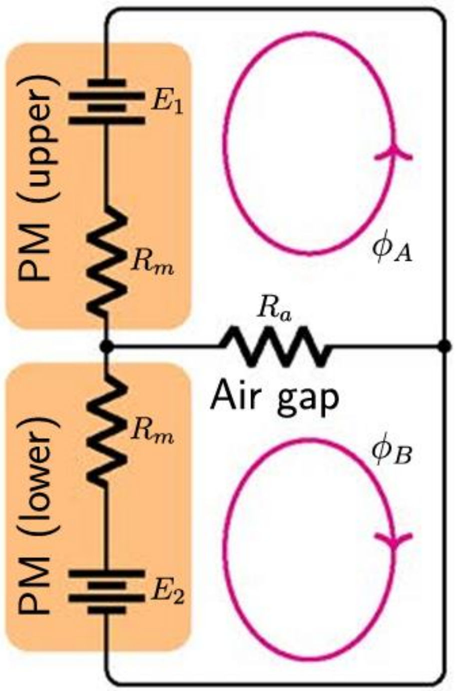




$$R_\mathrm{m} = \frac{\delta_\mathrm{m}}{\mu_\mathrm{m}\mu_0 S_\mathrm{m}}, \quad R_\mathrm{y} = \frac{\delta_\mathrm{y}}{\mu_\mathrm{y}\mu_0 S_\mathrm{y}}, \quad R_\mathrm{a} = \frac{\delta_\mathrm{a}}{\mu_0 S_\mathrm{a}},$$

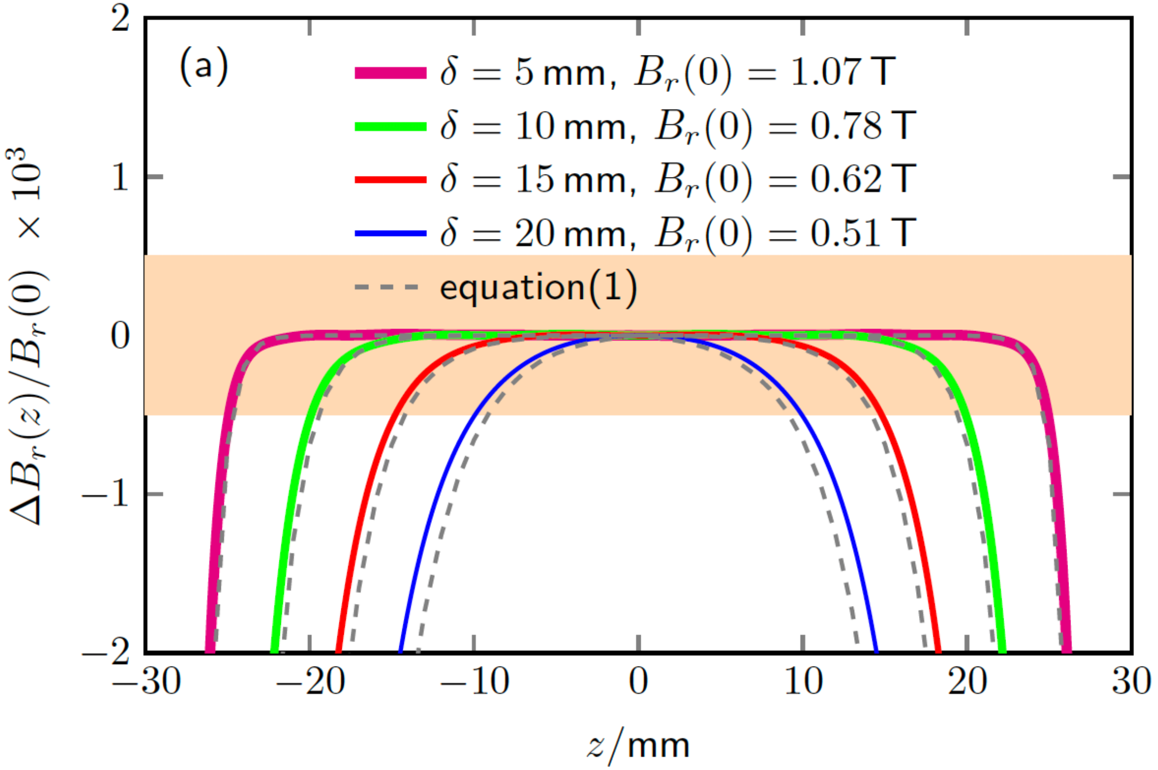
$$(R_\mathrm{m} + R_\mathrm{y} + R_\mathrm{a})\phi = -H_\mathrm{C}\delta_\mathrm{m}.$$

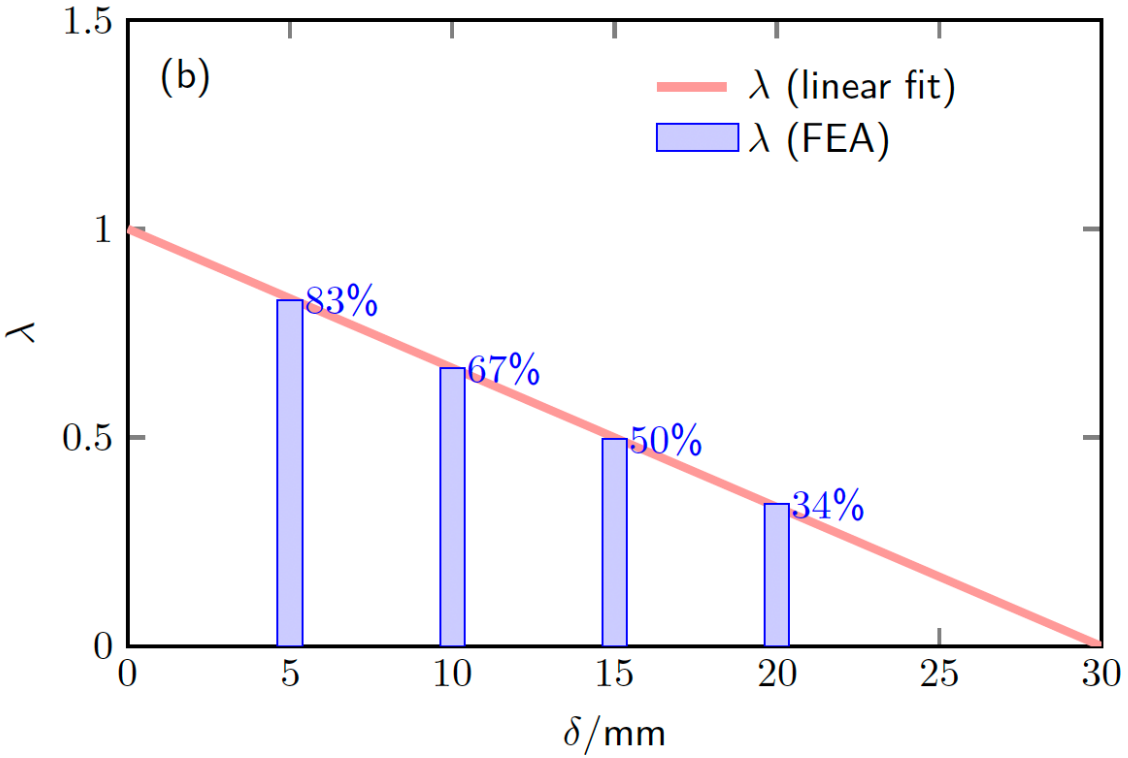
$$\phi = S_\mathrm{m} B_\mathrm{m} = B_\mathrm{a} S_\mathrm{a}$$

$$B_\mathrm{a} = \frac{-H_\mathrm{C}}{\frac{S_\mathrm{a}}{S_\mathrm{m}}\frac{1}{\mu_\mathrm{m}\mu_0} + \frac{\delta_\mathrm{a}}{\delta_\mathrm{m}}\frac{1}{\mu_0}} \approx \frac{-\mu_0 H_\mathrm{C}}{\frac{S_\mathrm{a}}{S_\mathrm{m}} + \frac{\delta_\mathrm{a}}{\delta_\mathrm{m}}} \approx \frac{1\ \mathrm{T}}{\frac{S_\mathrm{a}}{S_\mathrm{m}} + \frac{\delta_\mathrm{a}}{\delta_\mathrm{m}}}.$$

KB magnet design: *Improve field uniformity*

BIPM

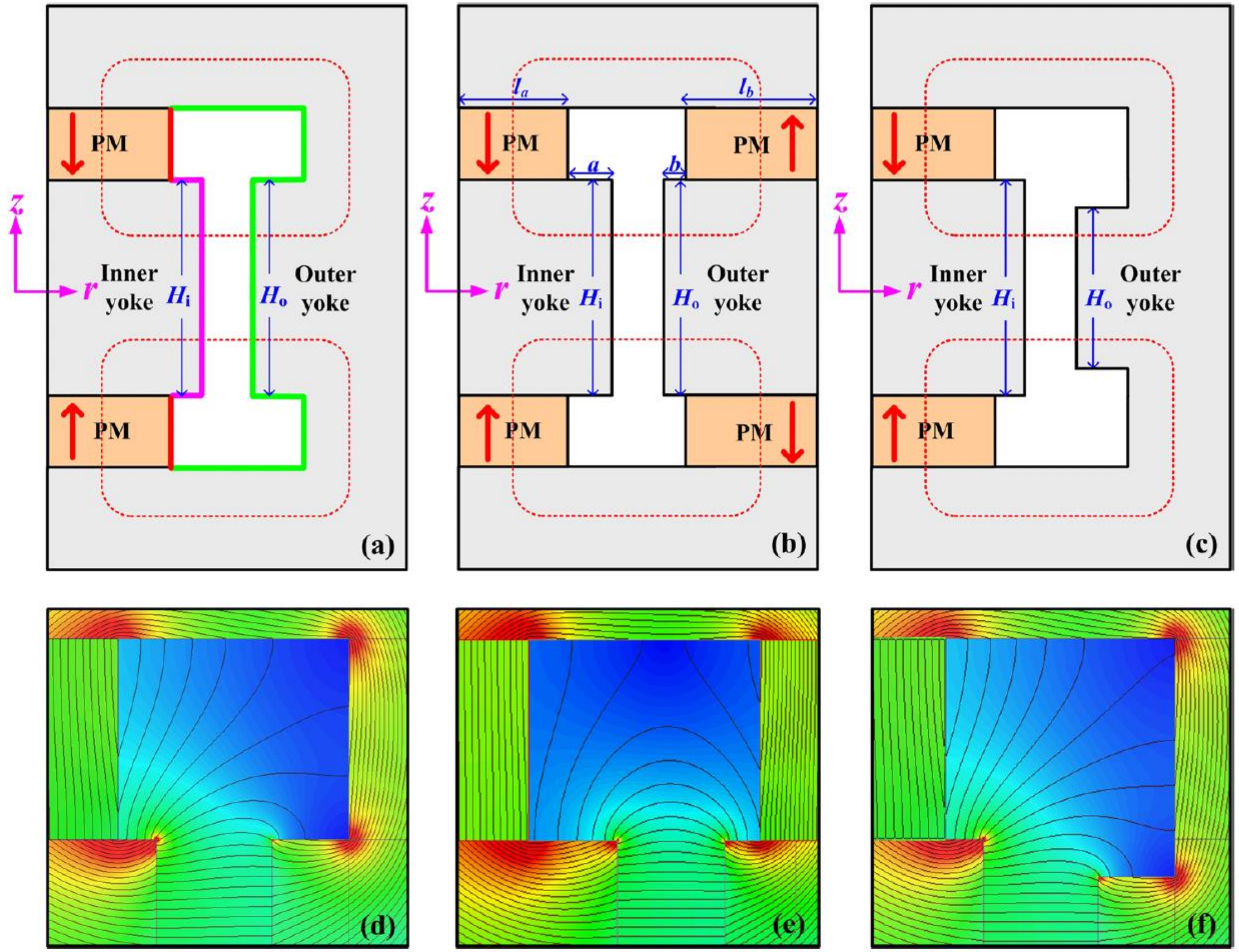


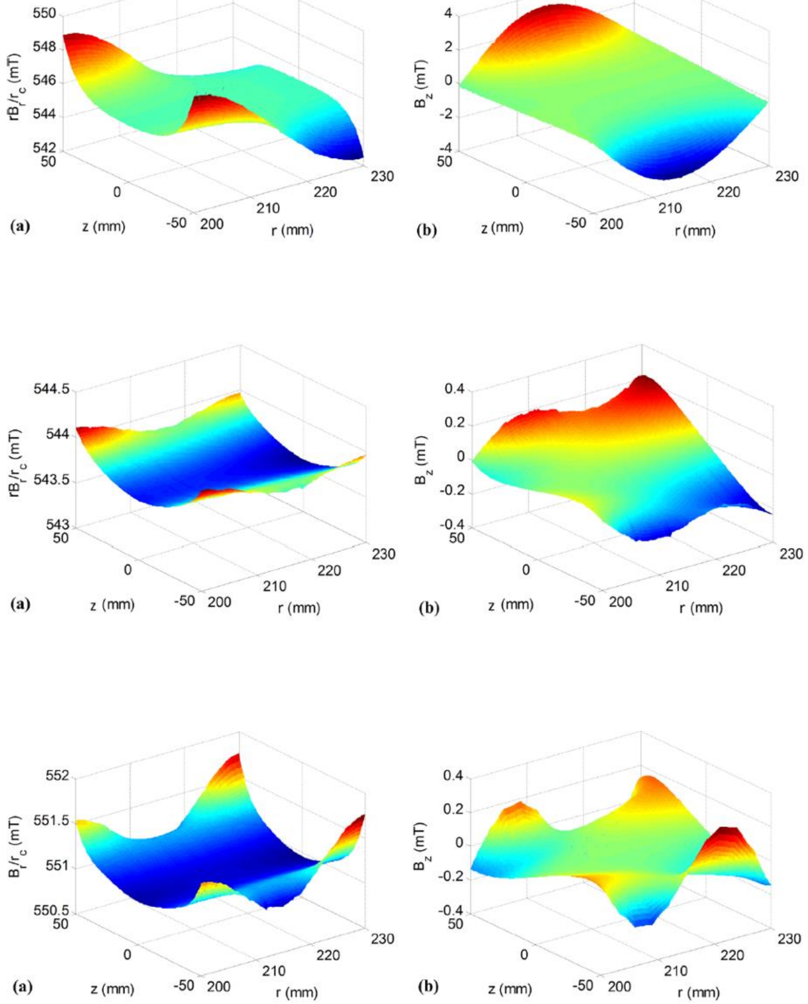


$$\frac{B_r(z)}{B_r(0)} - 1 = -\exp\left[-\left(1 + \frac{\pi(h_a - 2|z|)}{\delta_a}\right)\right] + \exp\left[-\left(1 + \frac{\pi h_a}{\delta_a}\right)\right],$$

KB magnet design: **Improve field uniformity**

A



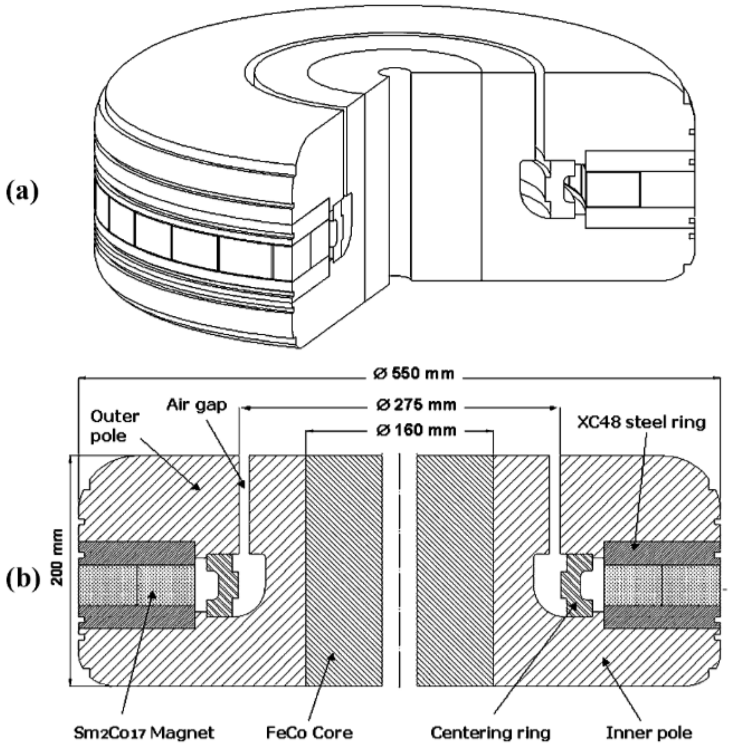


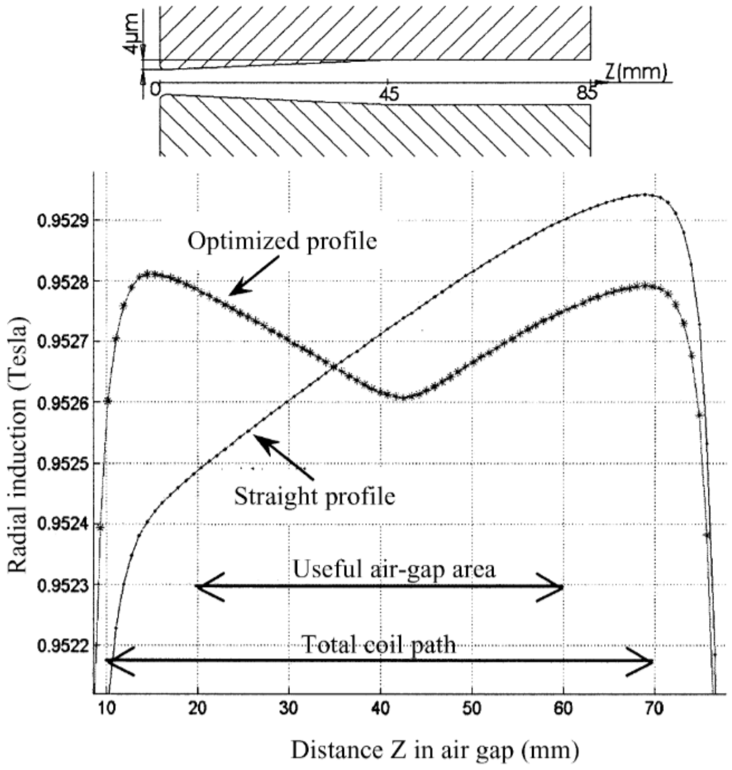
Li S, Schlamminger S 2017 Meas. Sci. Technol. 28 107001 (6pp)

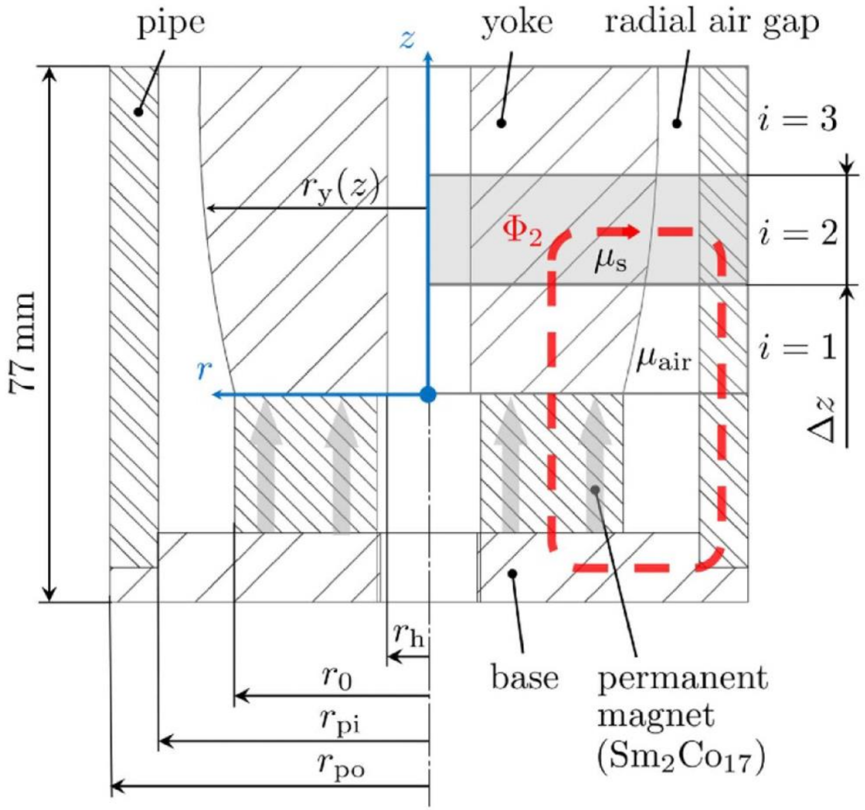
KB magnet design: *Improve field uniformity*

BIPM

B





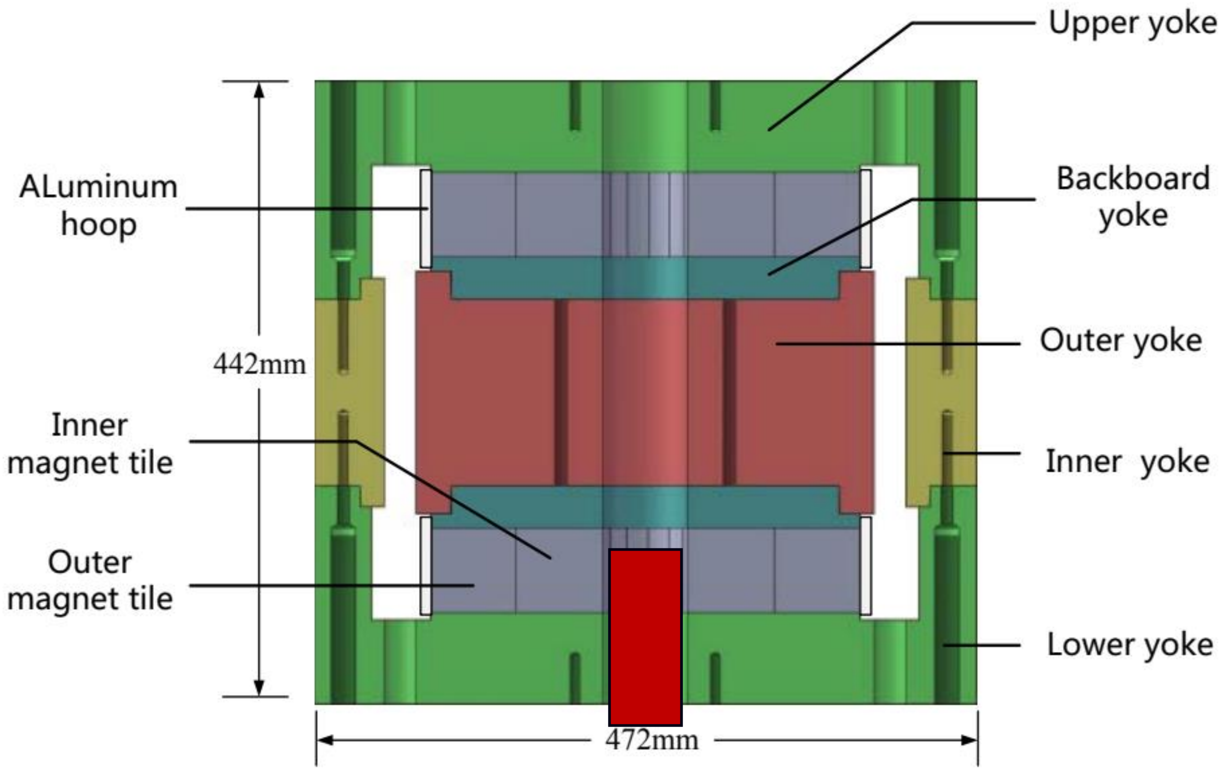


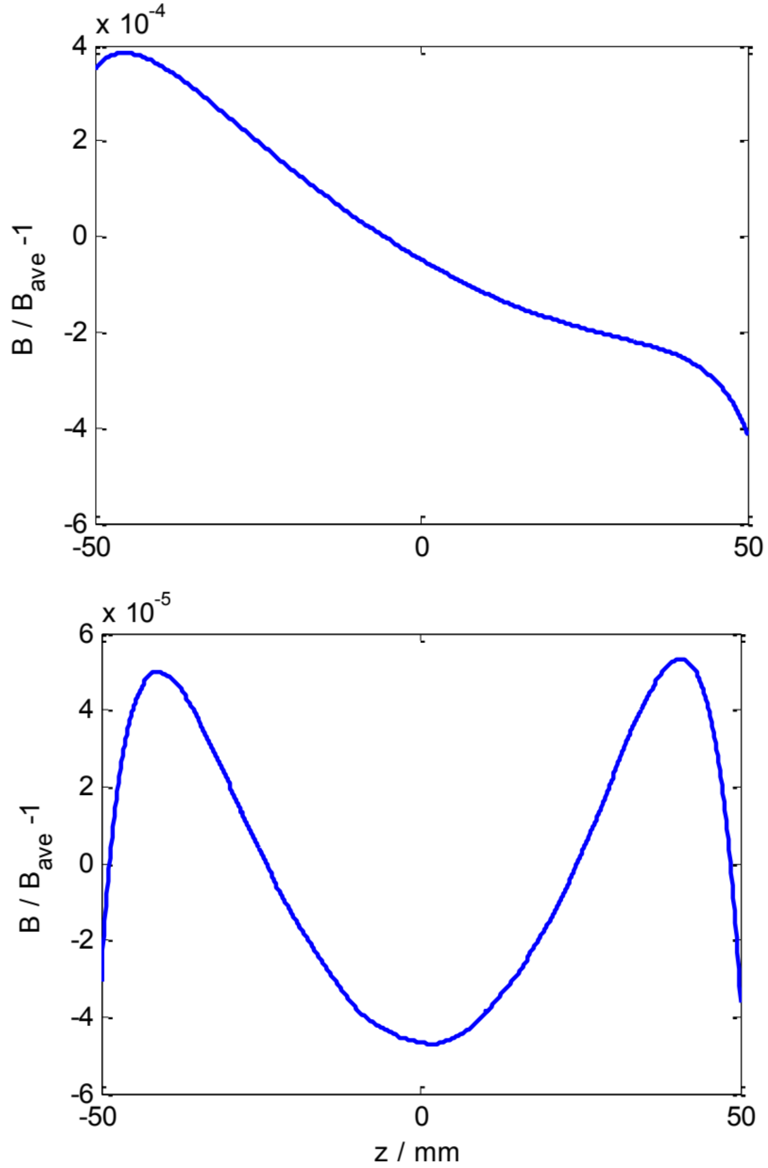
Li S, Schlamminger S 2017 Meas. Sci. Technol. 28 107001 (6pp)

Konrad J et al 2024 Meas. Sci. Technol. 35 105004

KB magnet design: ***Improve field uniformity***

C





HiperCo50 (saturation magnetic flux density is about 2.4T)

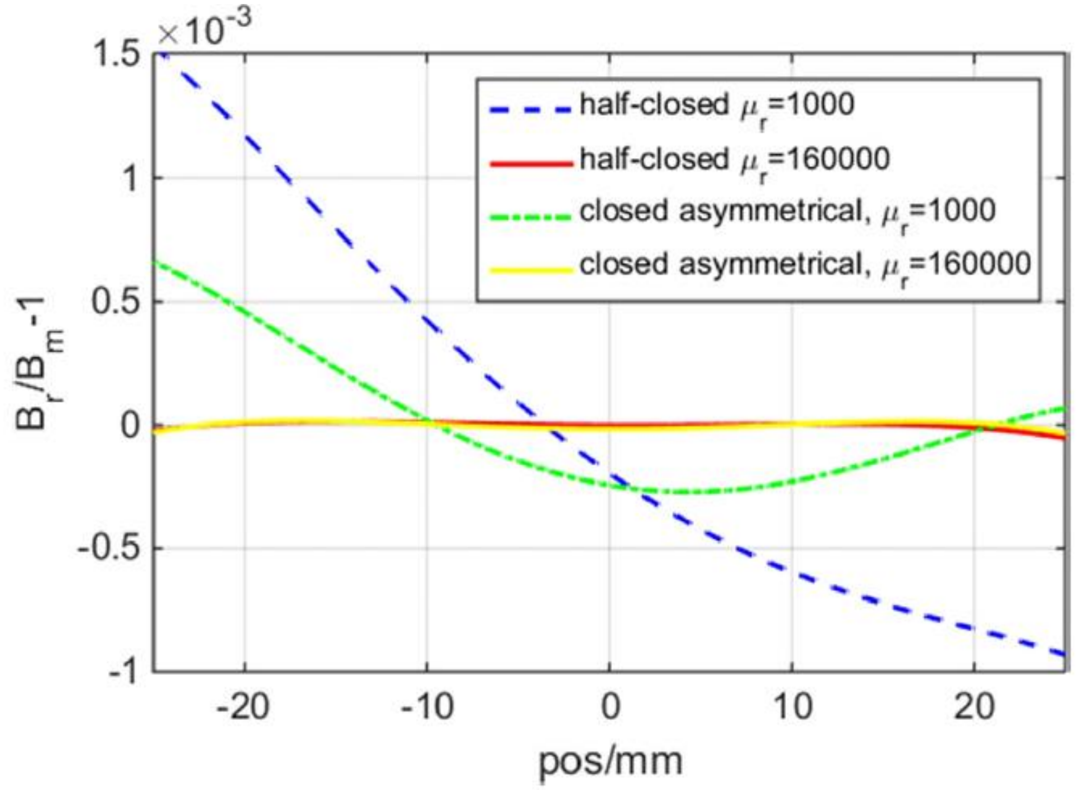
You Q et al CPEM2018

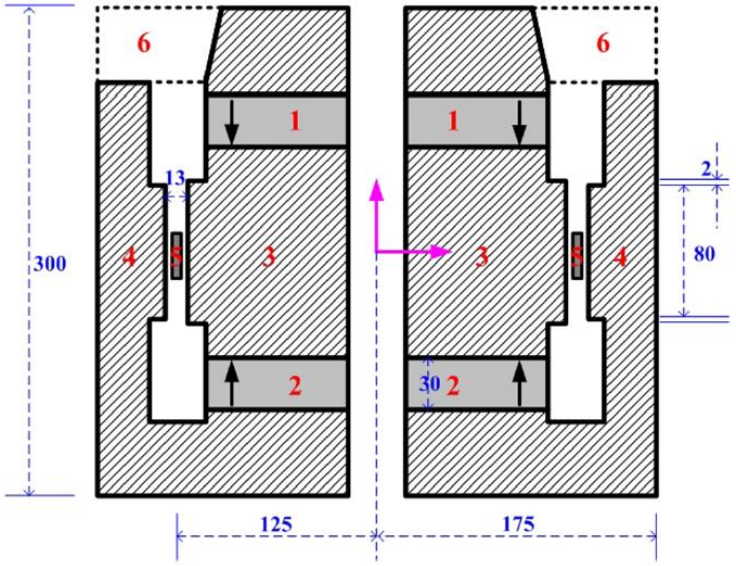
KB magnet design:

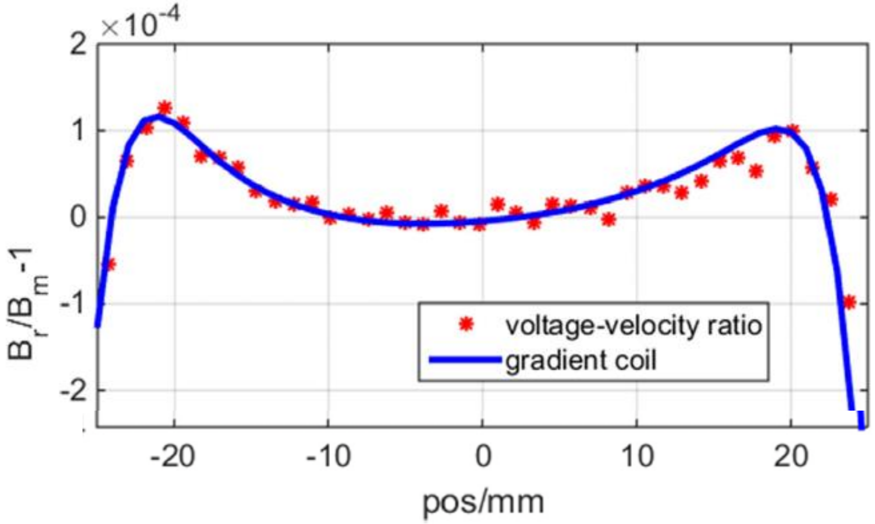
Improve field uniformity

BIPM

D



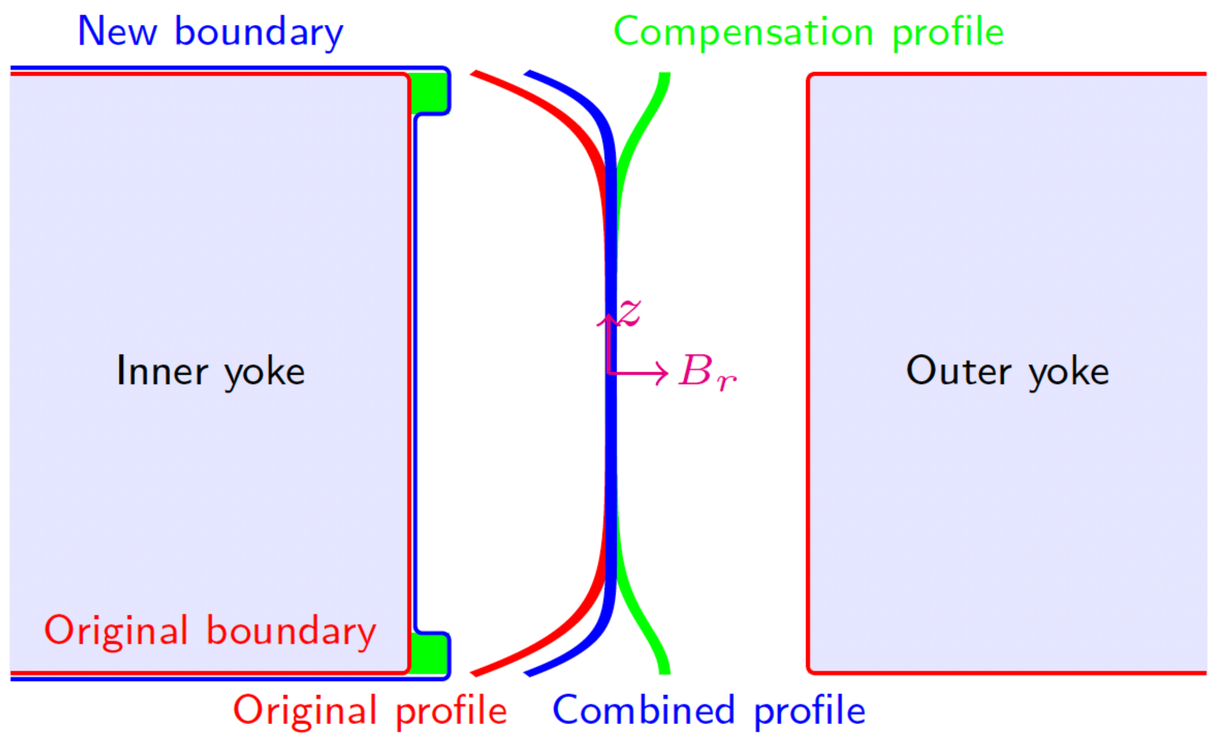


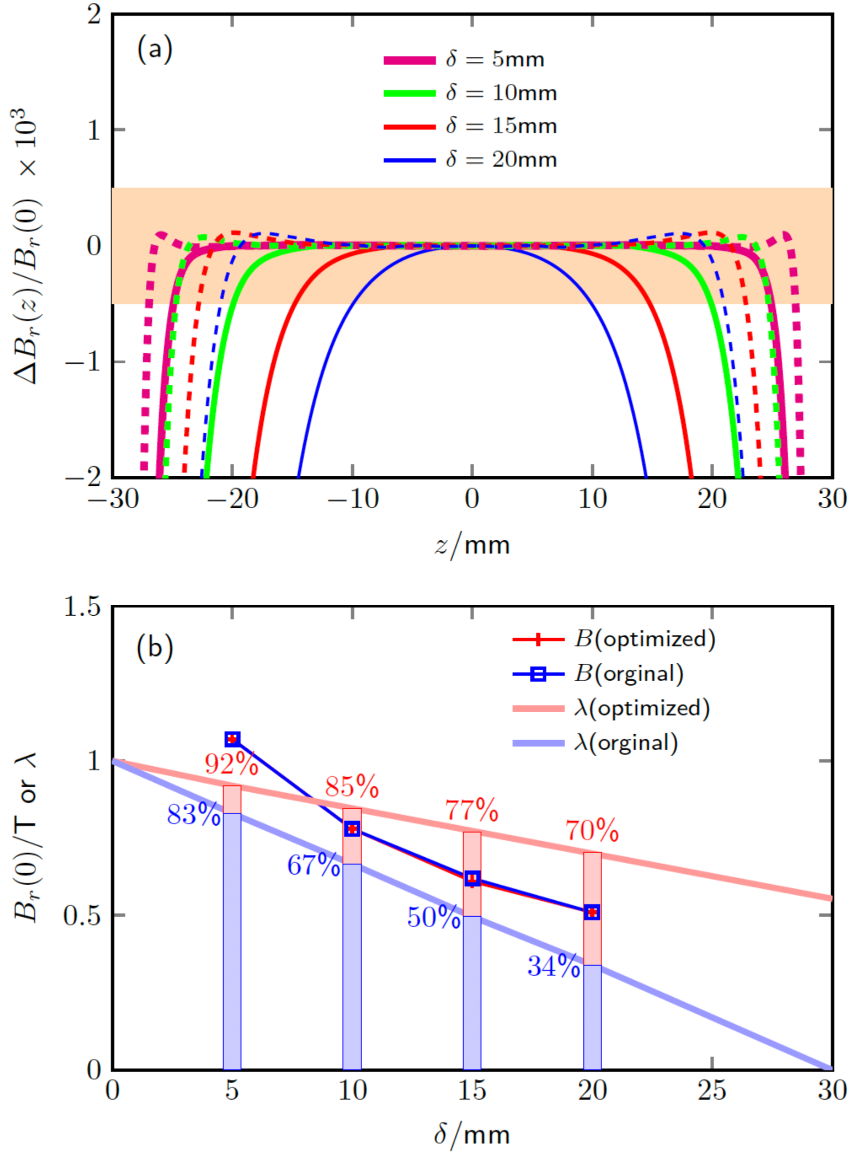


Li S et al 2017 Metrologia 54 (2017) 775–783

KB magnet design: ***Improve field uniformity***

E





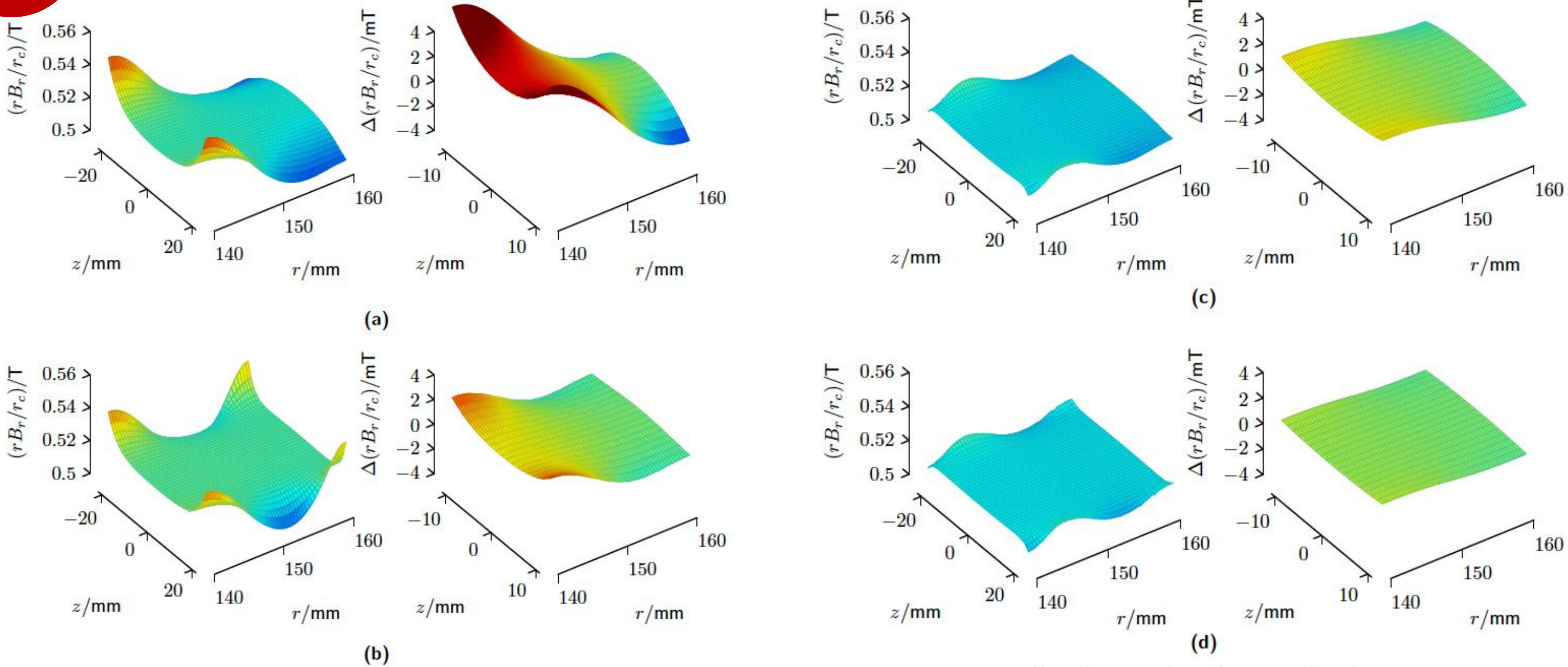
Li S et al 2020 IEEE TIM 69 7752–60

KB magnet design: *Improve field uniformity*

BIPM

E

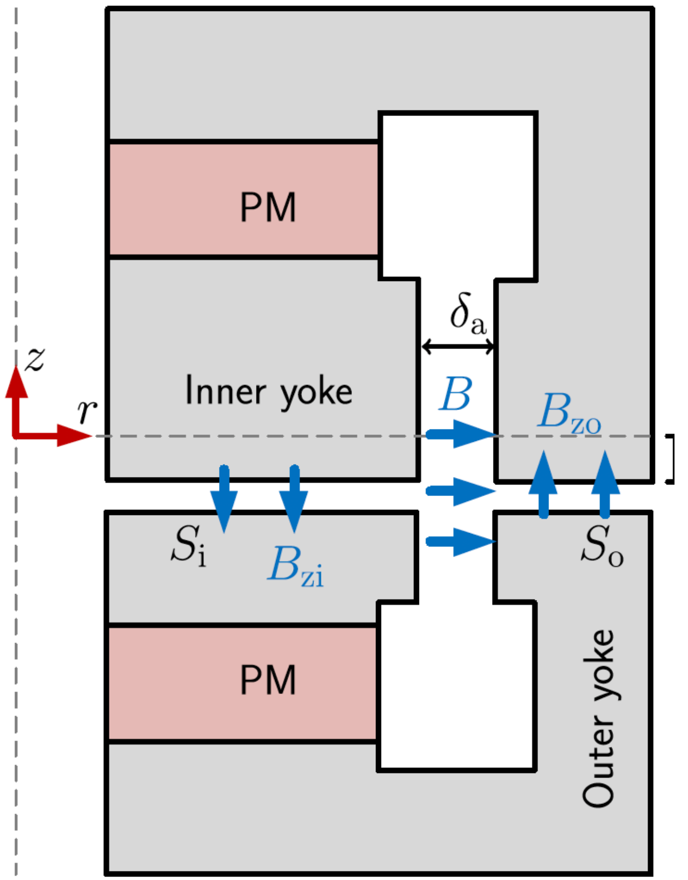
Inner yoke compensation

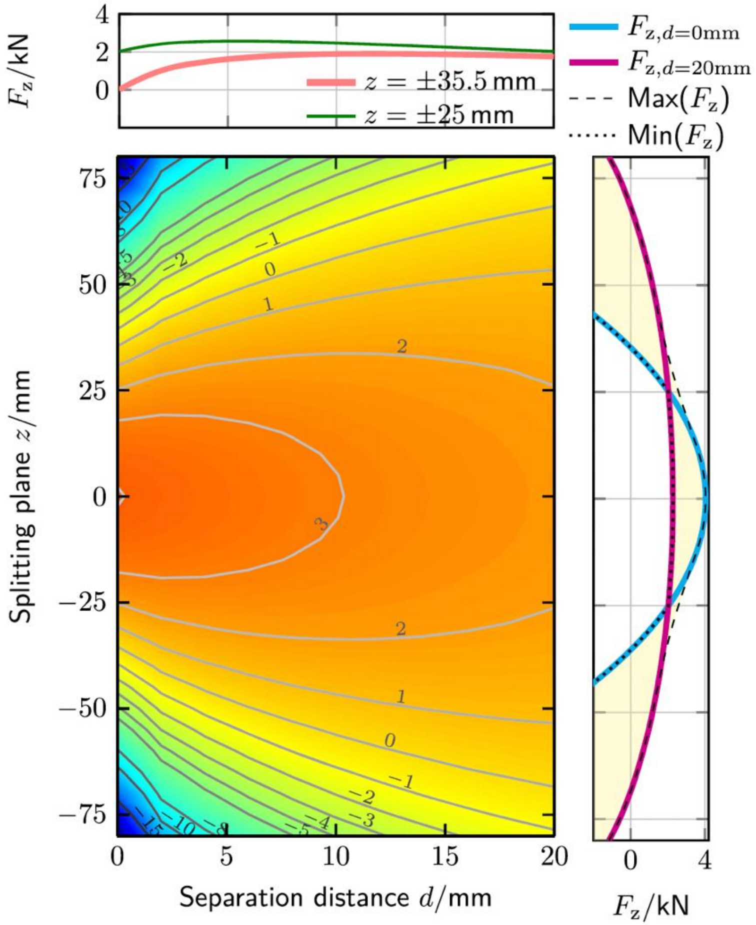


Both methods applied

Lowering outer yoke height

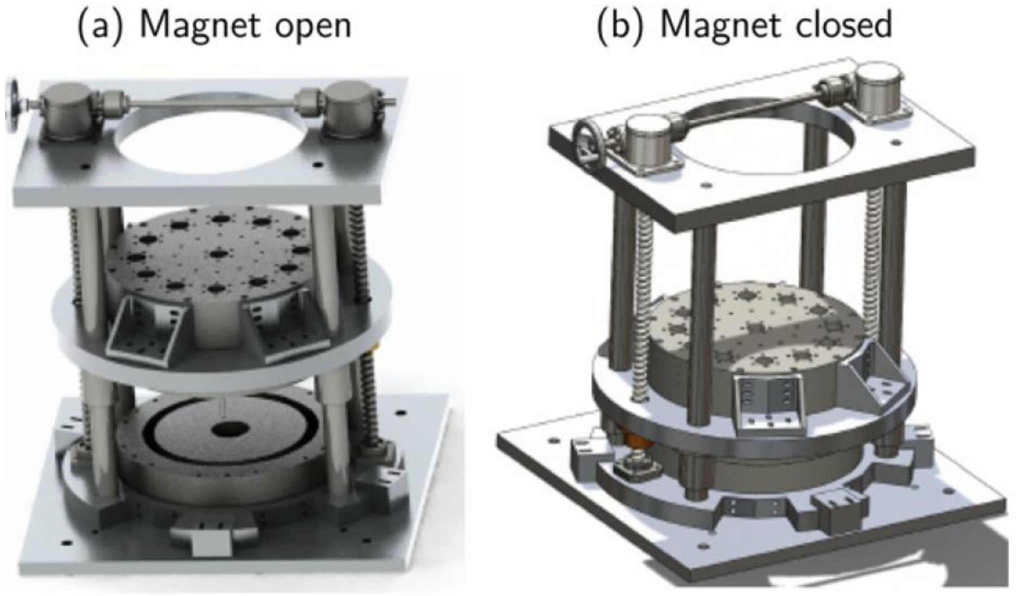
KB magnet design: *Splitting force*





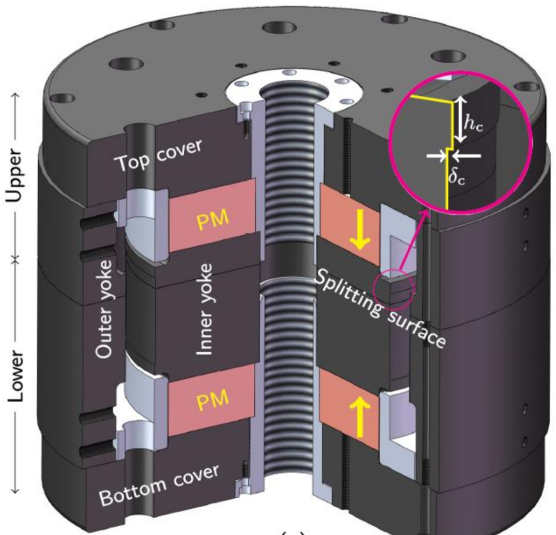
$$F_z(z) = \frac{\pi r_a B^2}{\mu_0}\left(\delta_a - \frac{2\pi r_a (S_i + S_o)}{S_i S_o} z^2\right)$$

Attractive OR Repulsive?

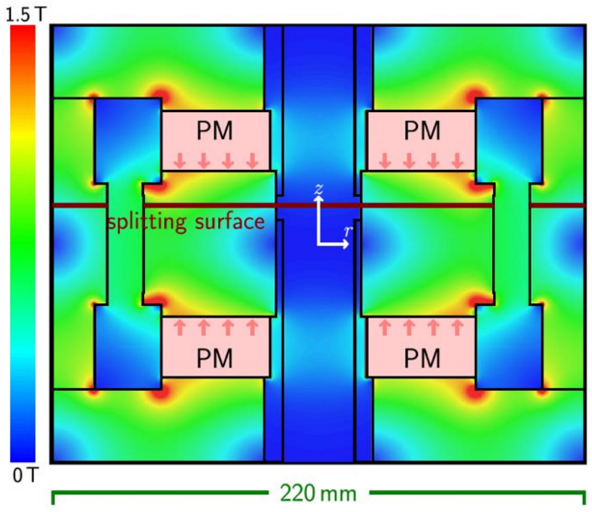


KB magnet design:

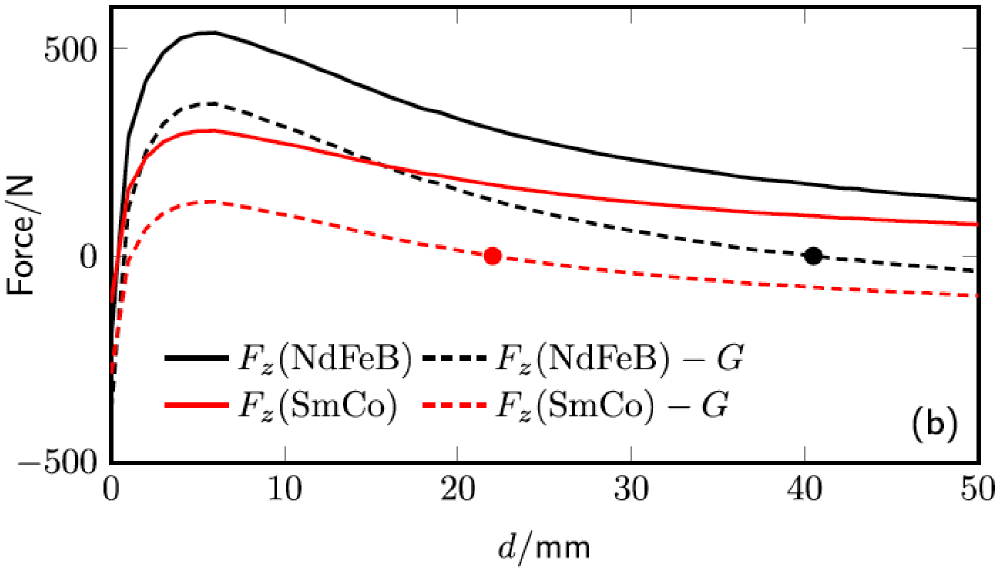
Splitting force



(a)



(b)



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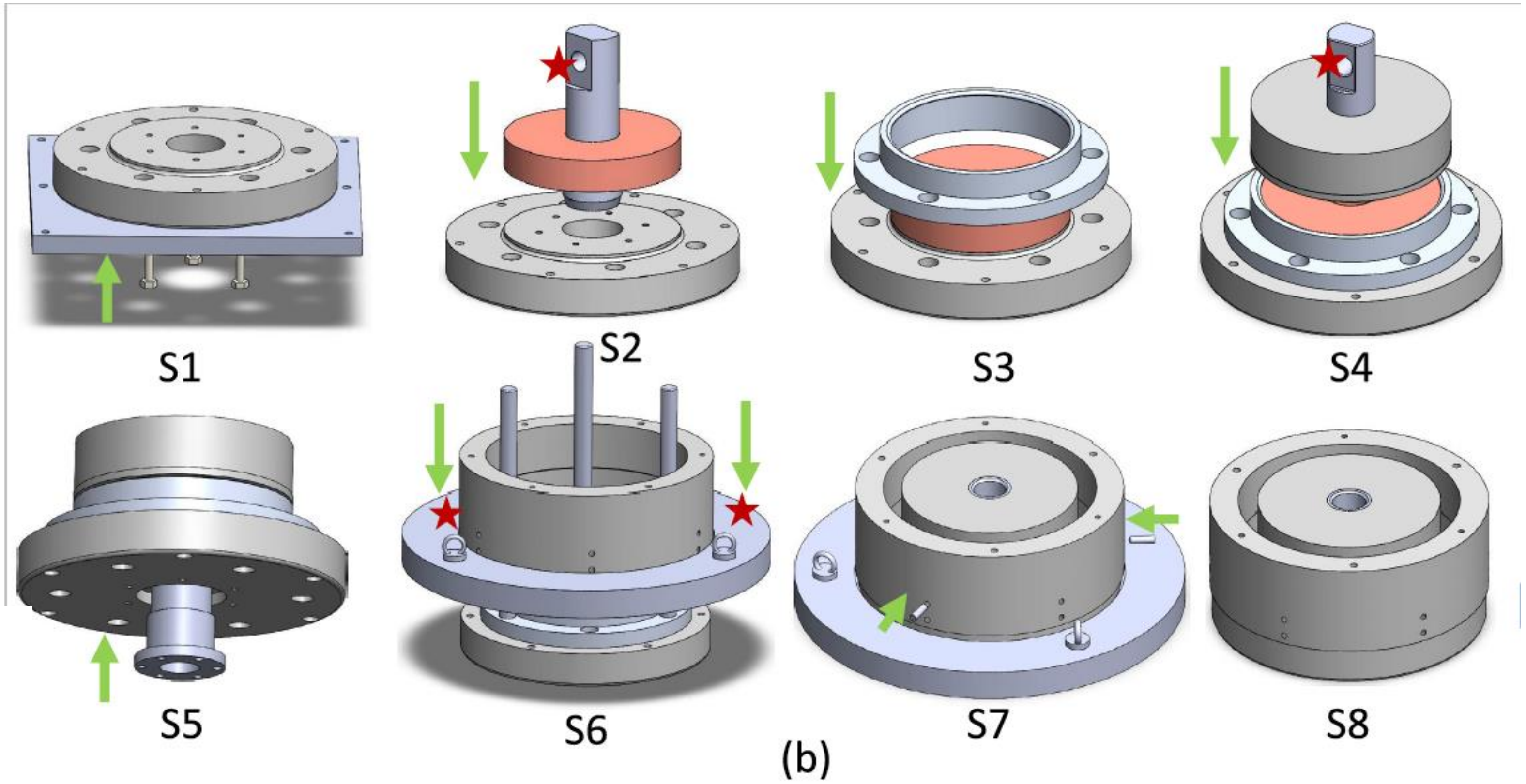
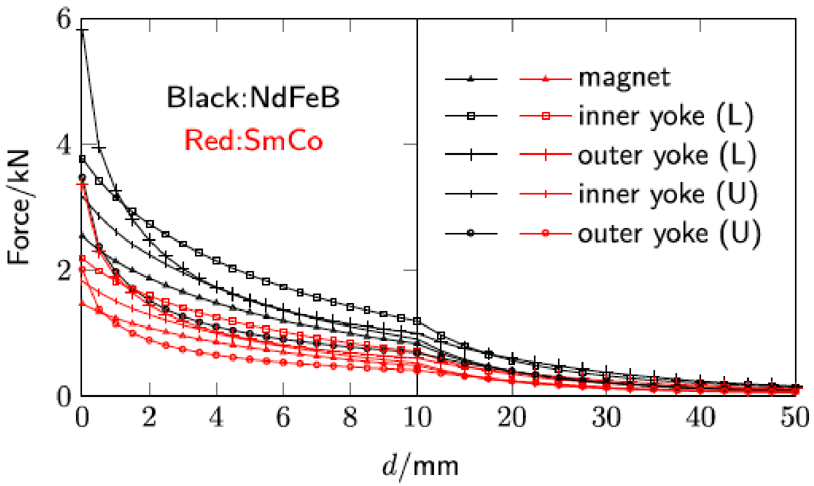
KB magnet design:

Installation force





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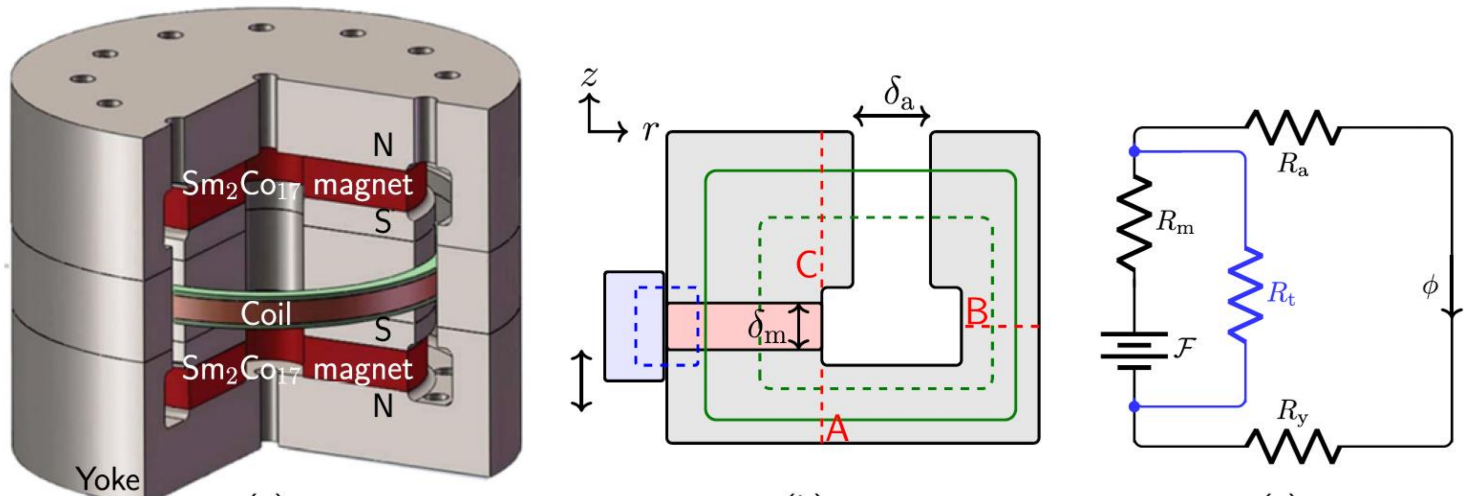
KB magnet design: *Thermal considerations*



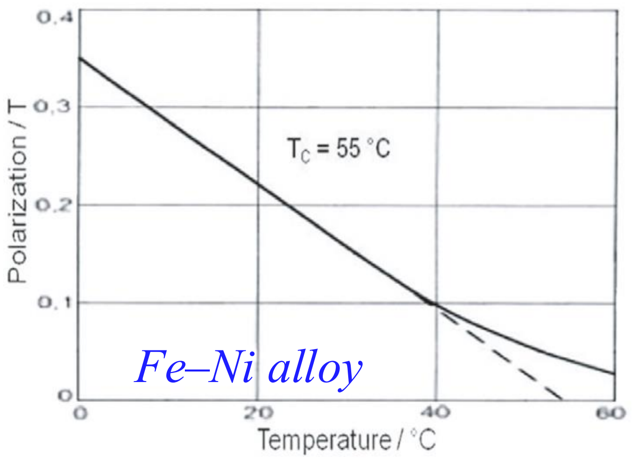
(a) (b) (c)

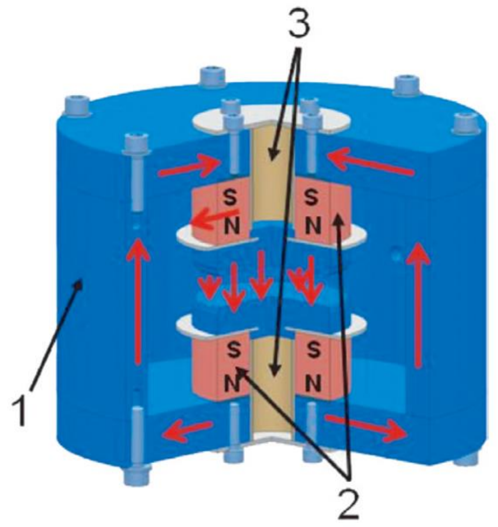
$$(\phi + \phi')R_m + \phi(R_a + R_y) = \mathcal{F}$$

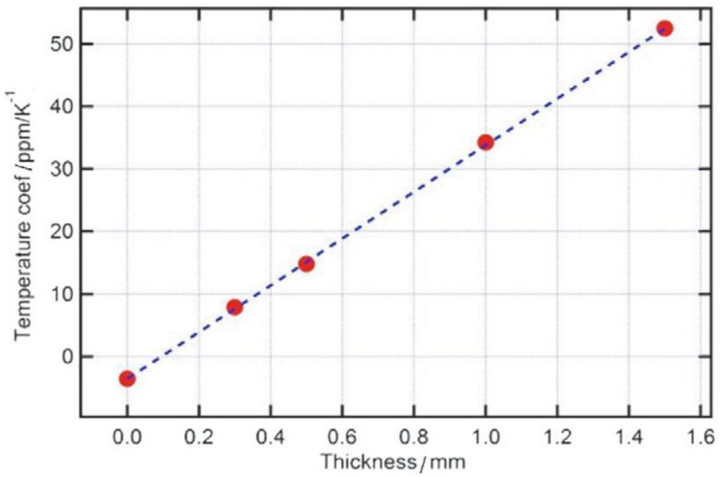
$$(\phi + \phi')R_m + \phi' R_t = \mathcal{F}.$$

$$\frac{1}{\mathcal{F}}\frac{\partial \mathcal{F}}{\partial T} = -\frac{1}{R_m + R_a}\frac{R_m R_a}{R_t^2}\frac{\partial R_t}{\partial T},$$

$$\left[\frac{1}{\mathcal{F}}\frac{\partial \mathcal{F}}{\partial T}\right] = -\frac{R_m R_a}{(R_m + R_a)R_t}\left[\frac{1}{R_t}\frac{\partial R_t}{\partial T}\right]$$







H Baumann *et al* 2013 *Metrologia* **50** 235

Outlines

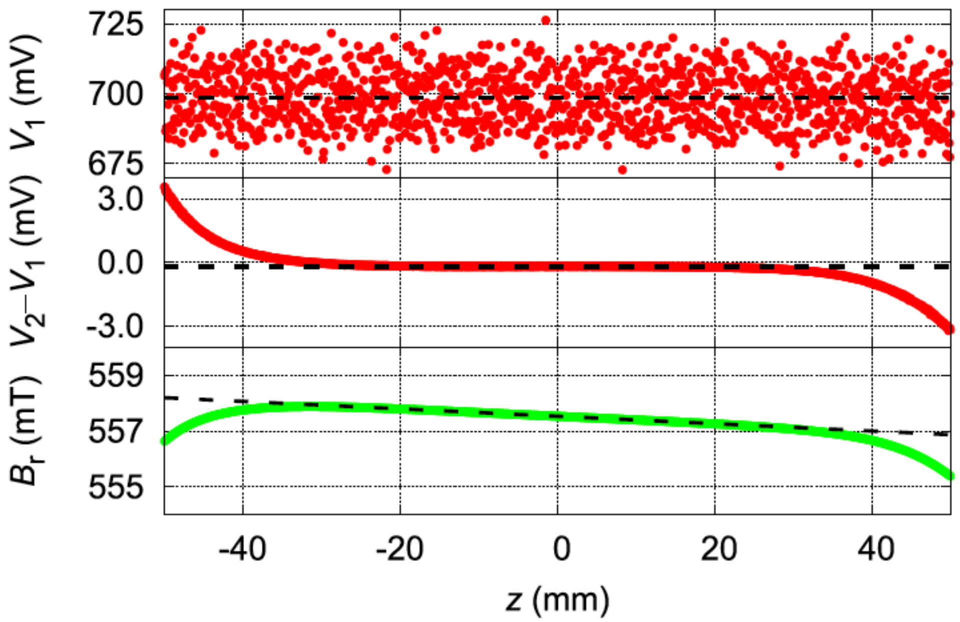
CCM

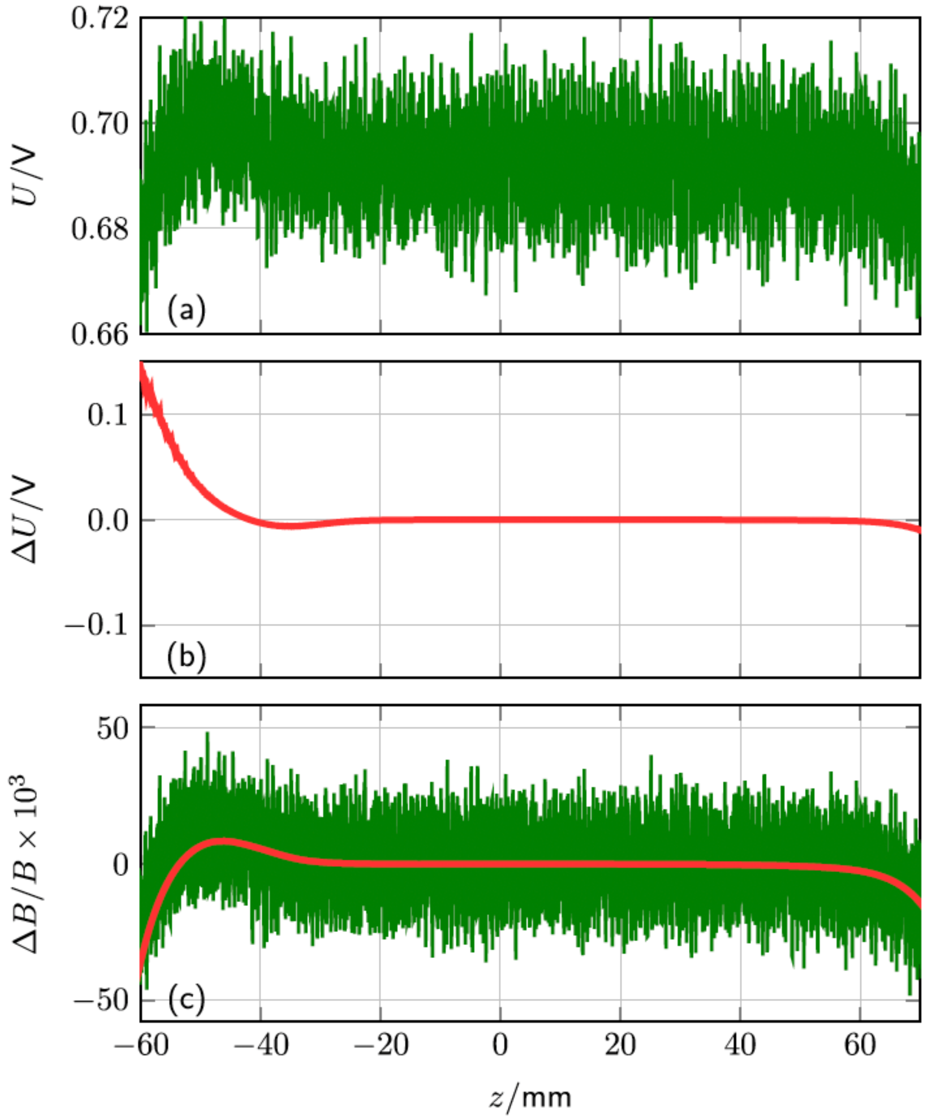
1. Magnetic basics in KB experiments
2. A Brief history KB magnet-coil designs
3. How to design a KB magnet system
4. Evaluation performance of a KB magnet
5. Systematic effects and how to reduce
6. Summary & outlook

Performance evaluation: *Magnetic profile*

$$\frac{V_1(z) - V_2(z)}{V_1(z)} = \frac{B_r(z) - B_r(z - \Delta z)}{B_r(z)} \approx \frac{\Delta z \frac{dB_r(z)}{dz}}{B_r(z)}.$$

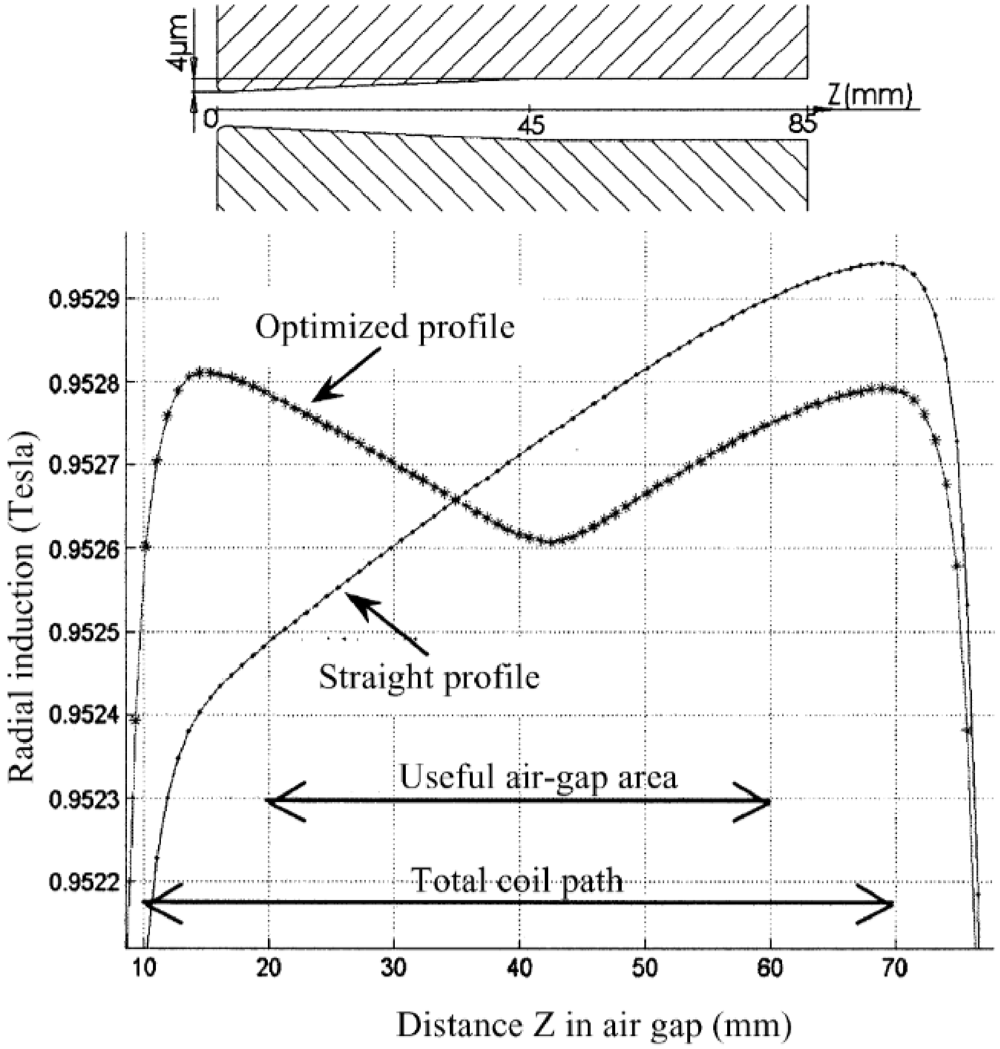
$$B_r(z) = \frac{\bar{B}_r}{\bar{V}_1 \Delta z} \int_b^z \left(V_1(z') - V_2(z')\right) dz' + O$$



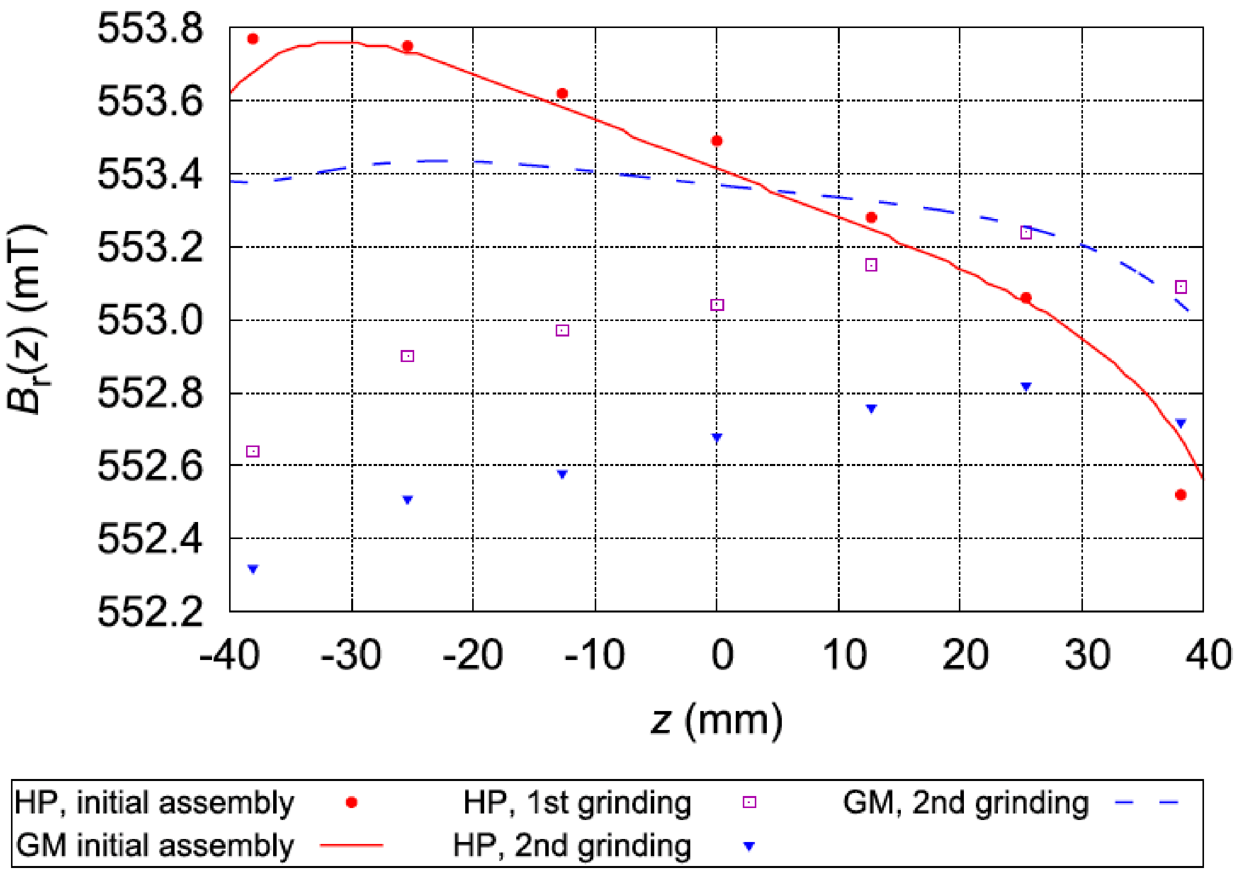


Seifert F et al 2014 IEEE TIM 63 3027

Performance evaluation: *Flattening profile*

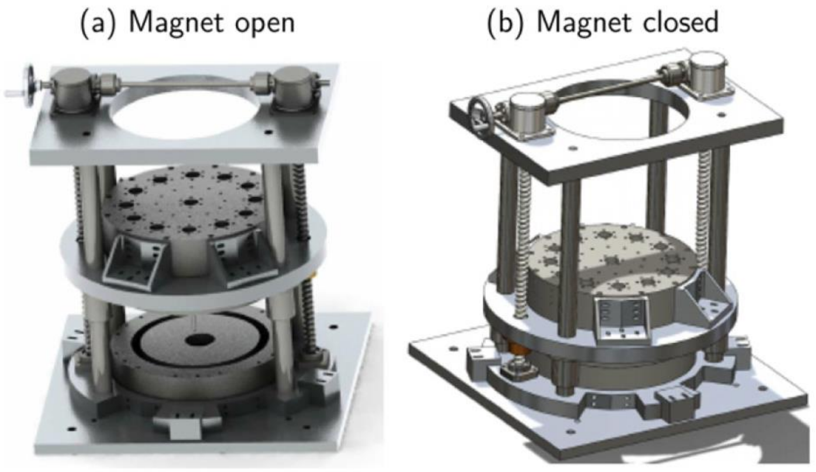


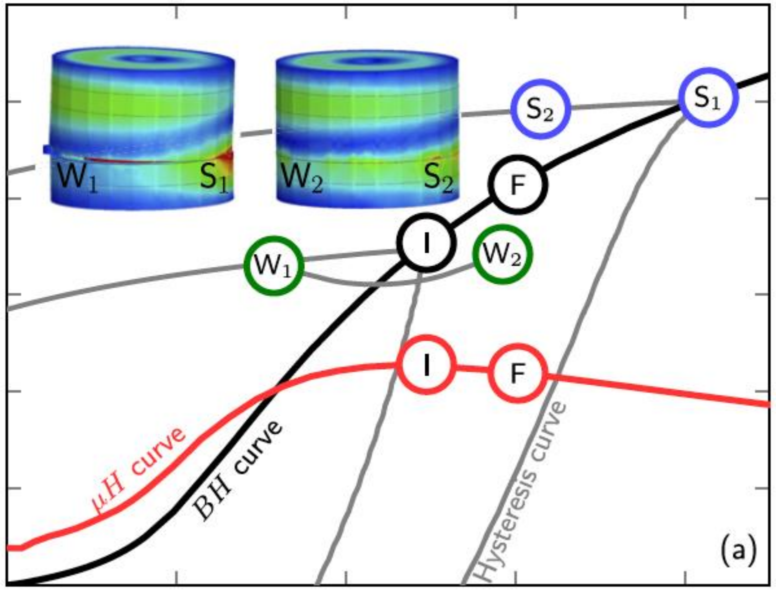
Gournay P et al 2005 IEEE TIM 54 742–5

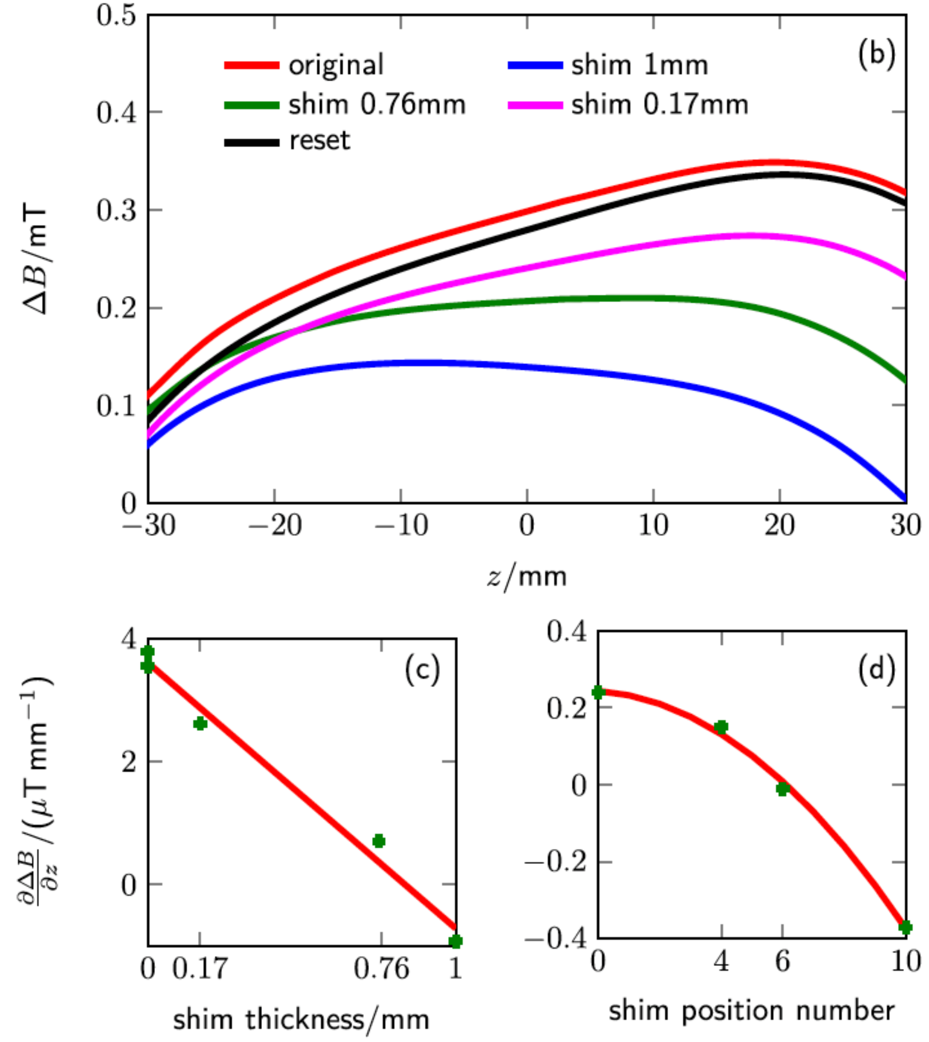


Seifert F et al 2014 IEEE TIM 63 3027

Performance evaluation: *Flattening profile*

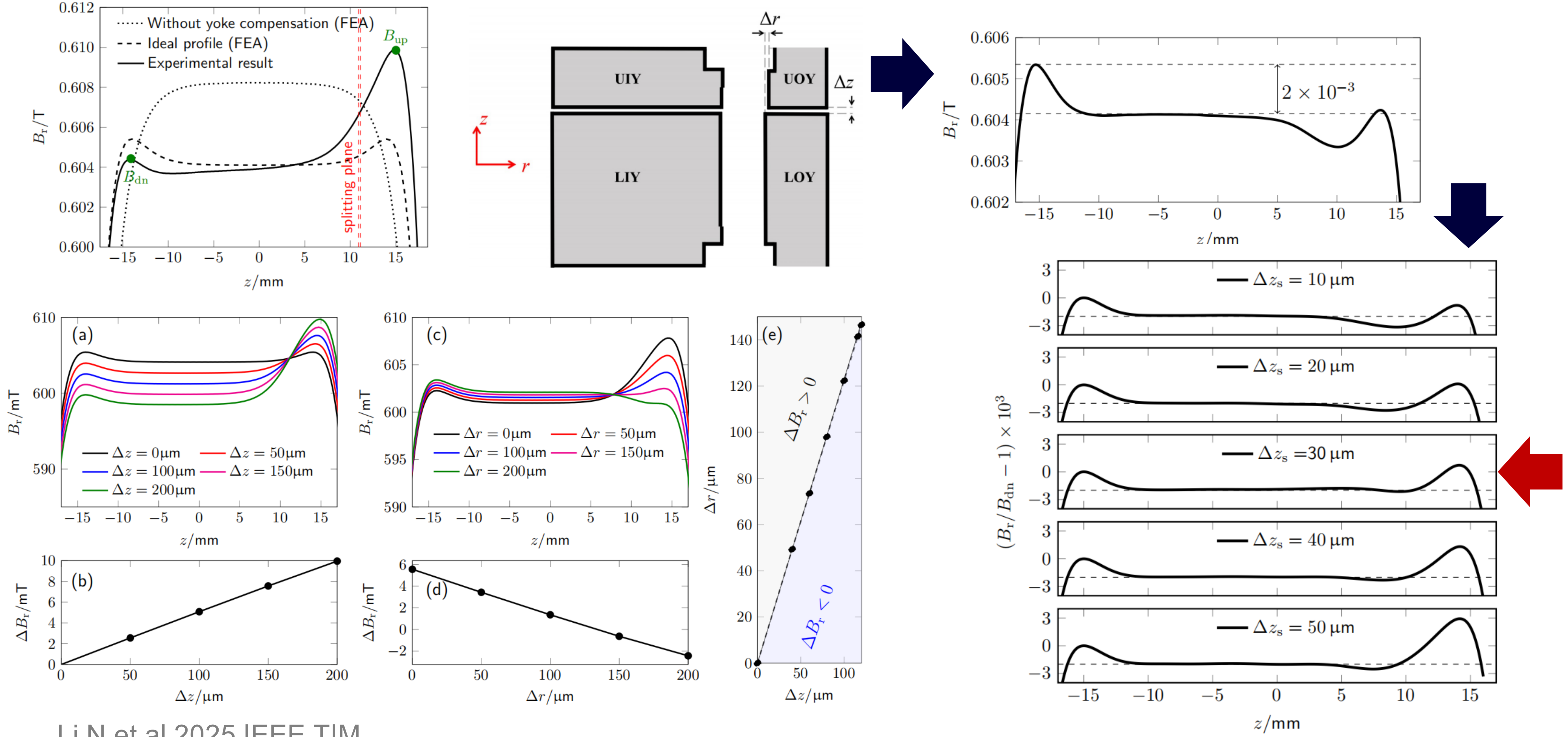






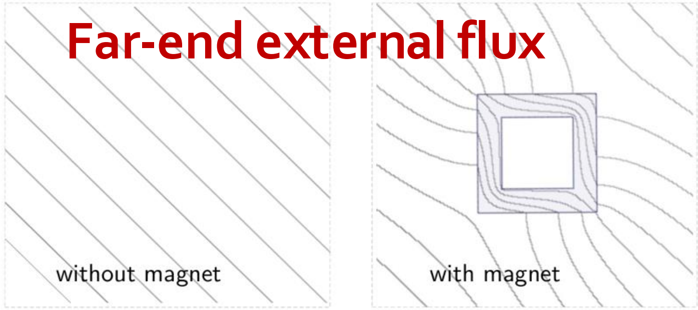
Seifert F et al 2014 IEEE TIM 63 3027

Performance evaluation: *Flattening profile*

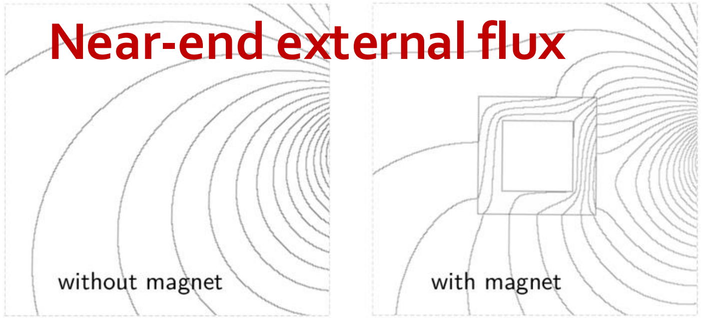


Li N et al 2025 IEEE TIM

Performance evaluation: *Shielding performance*

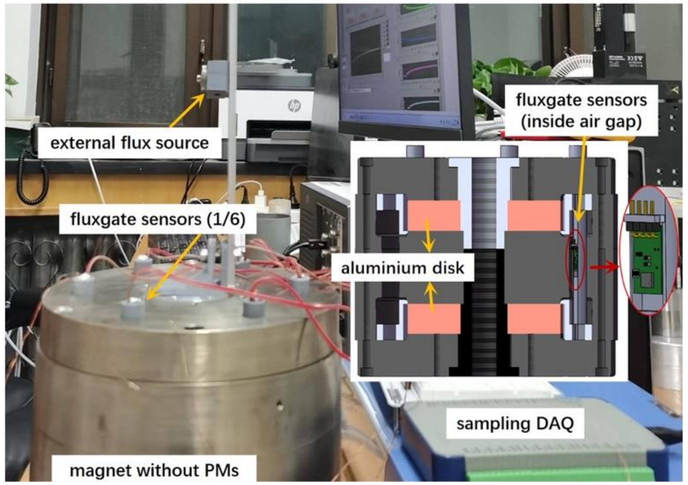


(a) far-end magnetic flux source

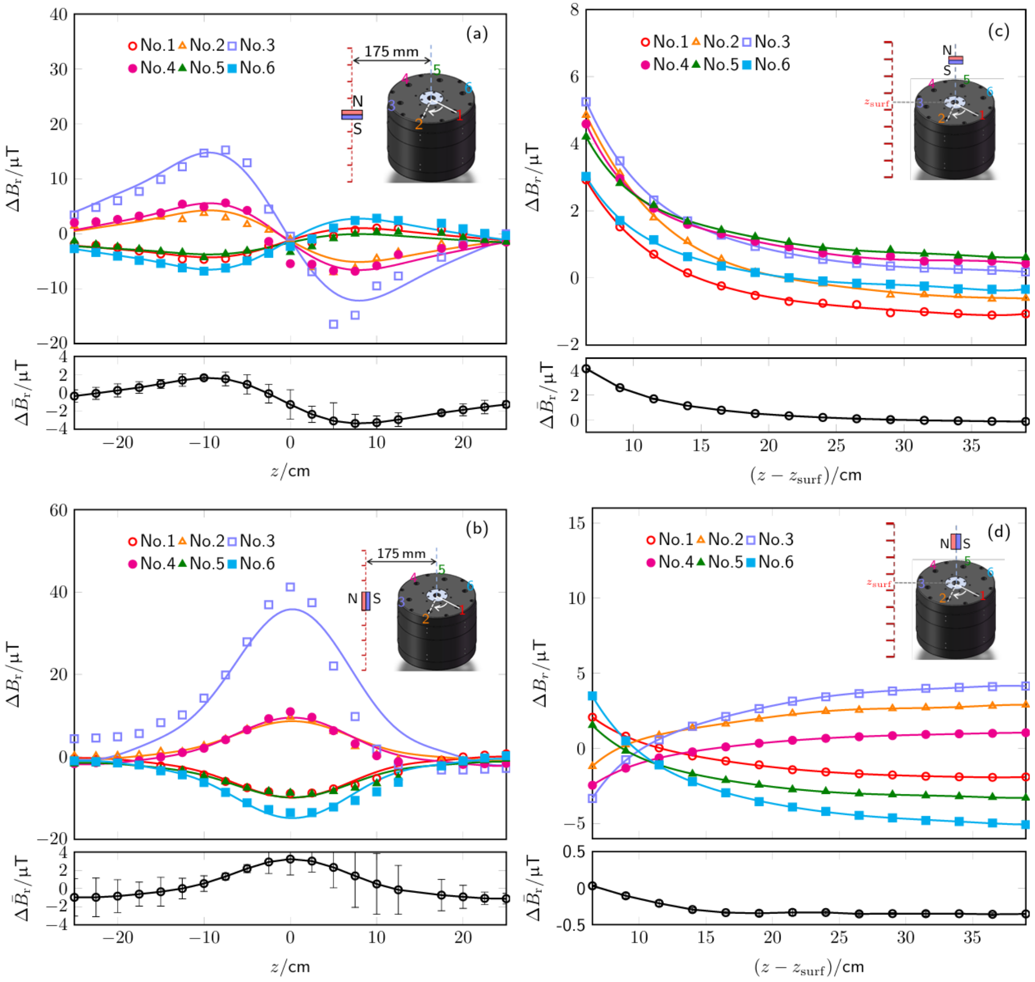


(b) near-end magnetic flux source

$$\varepsilon = \frac{\Delta m}{m} = \frac{B(z_\mathrm{w}) + \Delta\bar{B}_\mathrm{w}(z_\mathrm{w})}{B(z_\mathrm{w}) + \Delta\bar{B}_\mathrm{v}(z_\mathrm{w})} \approx \frac{\Delta\bar{B}_\mathrm{w}(z_\mathrm{w}) - \Delta\bar{B}_\mathrm{v}(z_\mathrm{w})}{B(z_\mathrm{w})}.$$



Type	$\gamma_{\max}$, FEA, $\mu_r = 1000$	$\gamma_{\max}$, Exp. without PMs	$\gamma_{\max}$, KB working status
$\mathcal{V}^{r=175\,\mathrm{mm}}_{z=-75\,\mathrm{mm}}$	7.4×10^{-5}	5.9×10^{-5}	6.0×10^{-6}
$\mathcal{H}^{r=175\,\mathrm{mm}}_{z=0\,\mathrm{mm}}$	7.7×10^{-5}	1.4×10^{-4}	1.4×10^{-5}
$\mathcal{V}^{r=0\,\mathrm{mm}}_{z=155\,\mathrm{mm}}$	3.9×10^{-5}	2.0×10^{-5}	2.0×10^{-6}
$\mathcal{H}^{r=0\,\mathrm{mm}}_{z=155\,\mathrm{mm}}$	2.4×10^{-5}	1.3×10^{-5}	1.4×10^{-6}



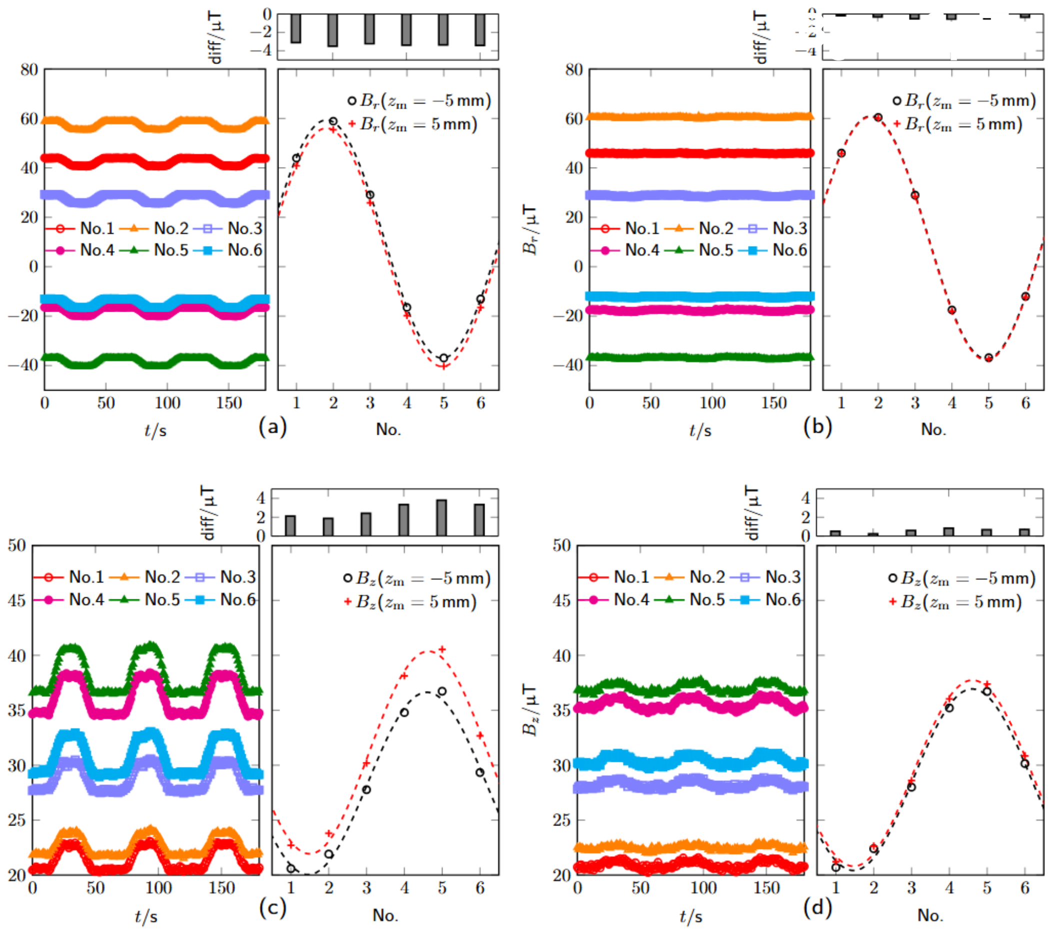
Ma Y et al 2025 IEEE TIM

Performance evaluation: *Shielding performance*

BIPM

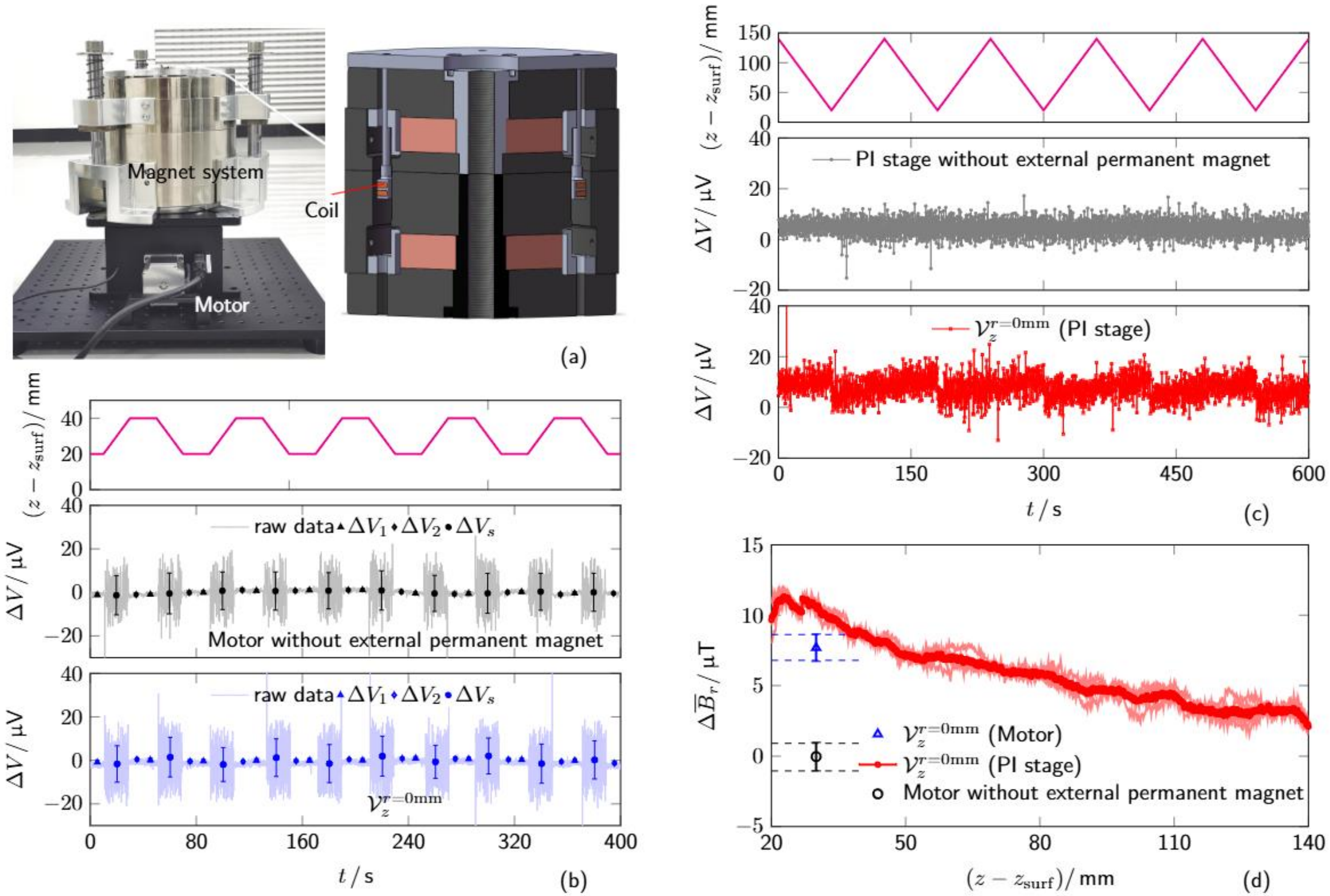
Radial

Vertical



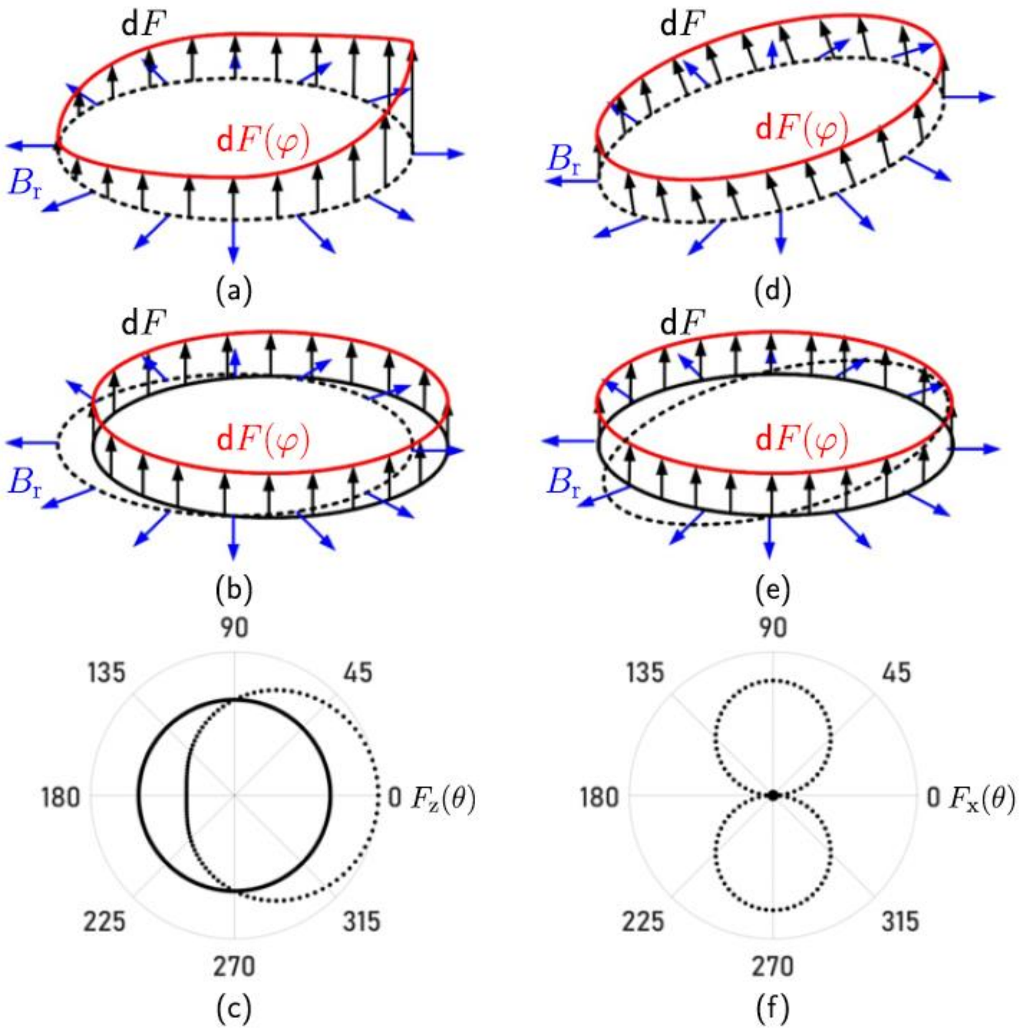
Move magnet

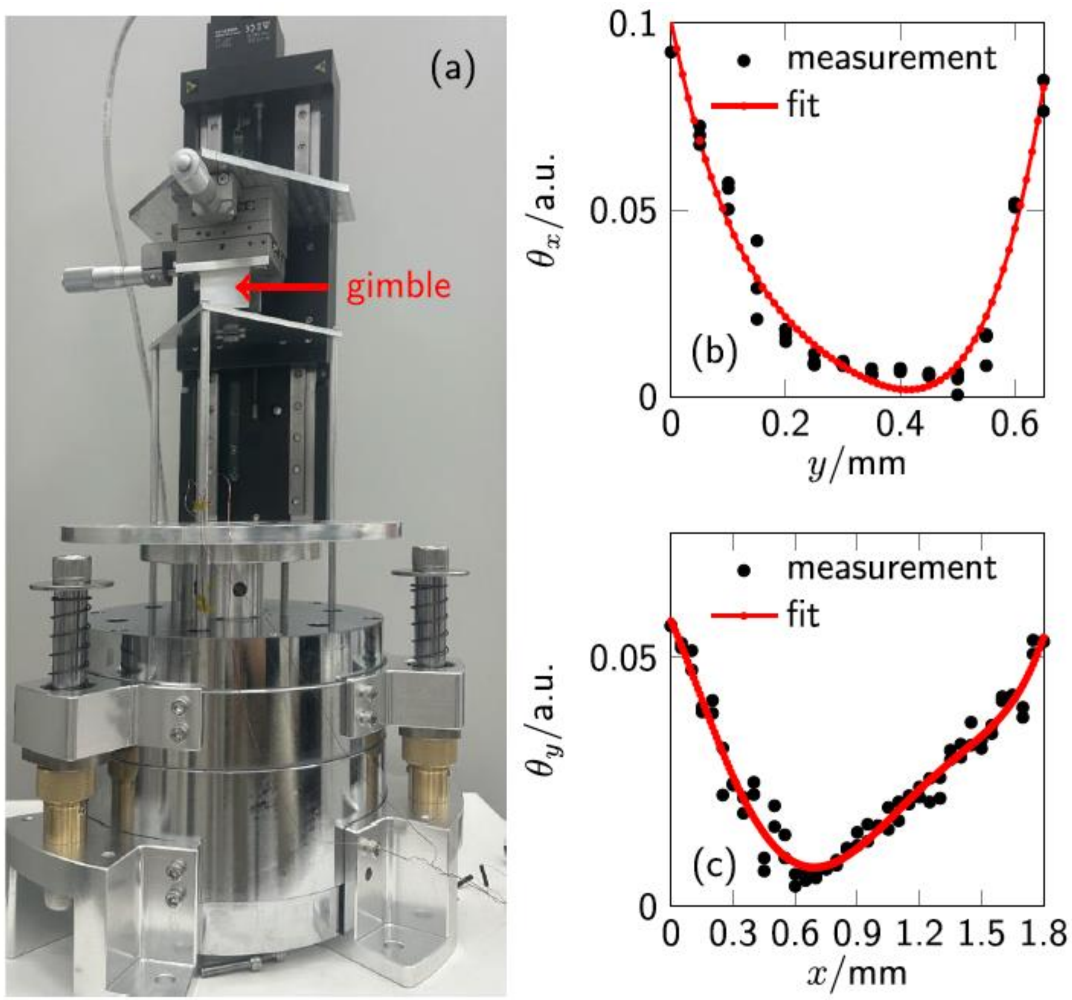
Move magnet & sensors



Ma Y et al 2025 IEEE TIM

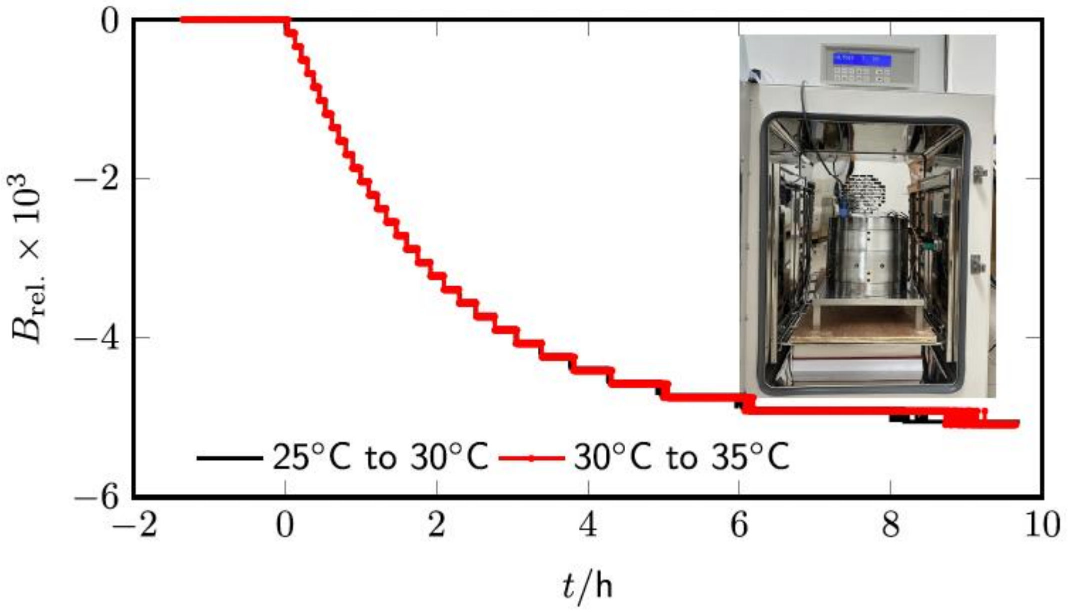
Performance evaluation: *Meet alignment range*

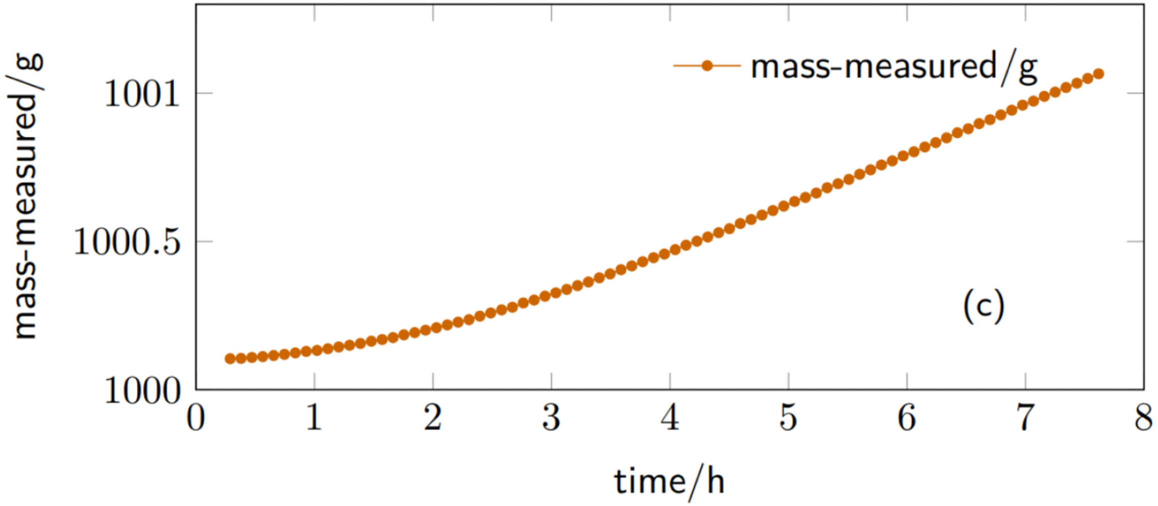


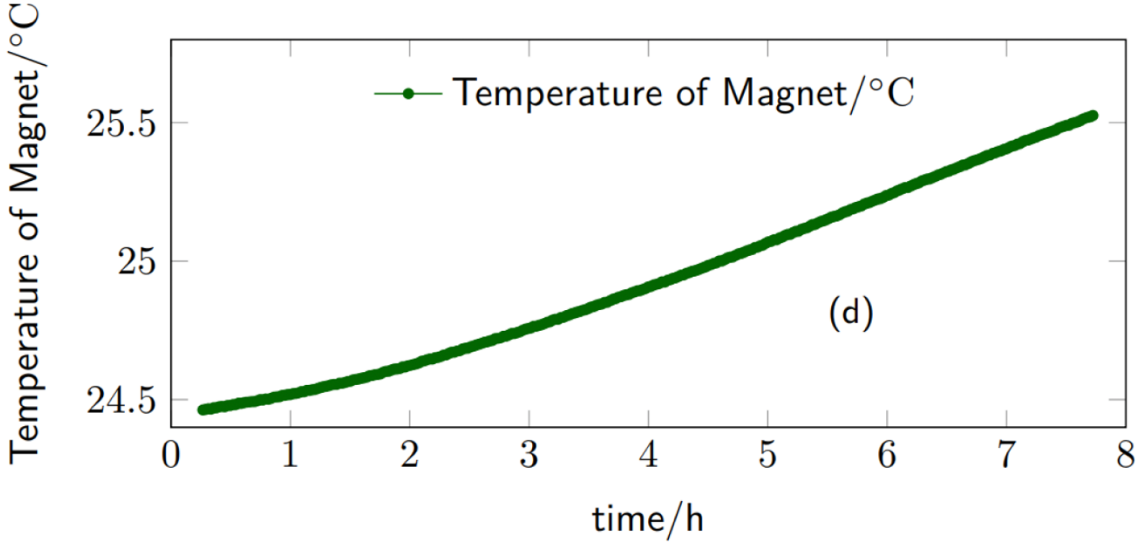


Ma Y et al 2025 IEEE TIM

Performance evaluation: *Tc measurement*







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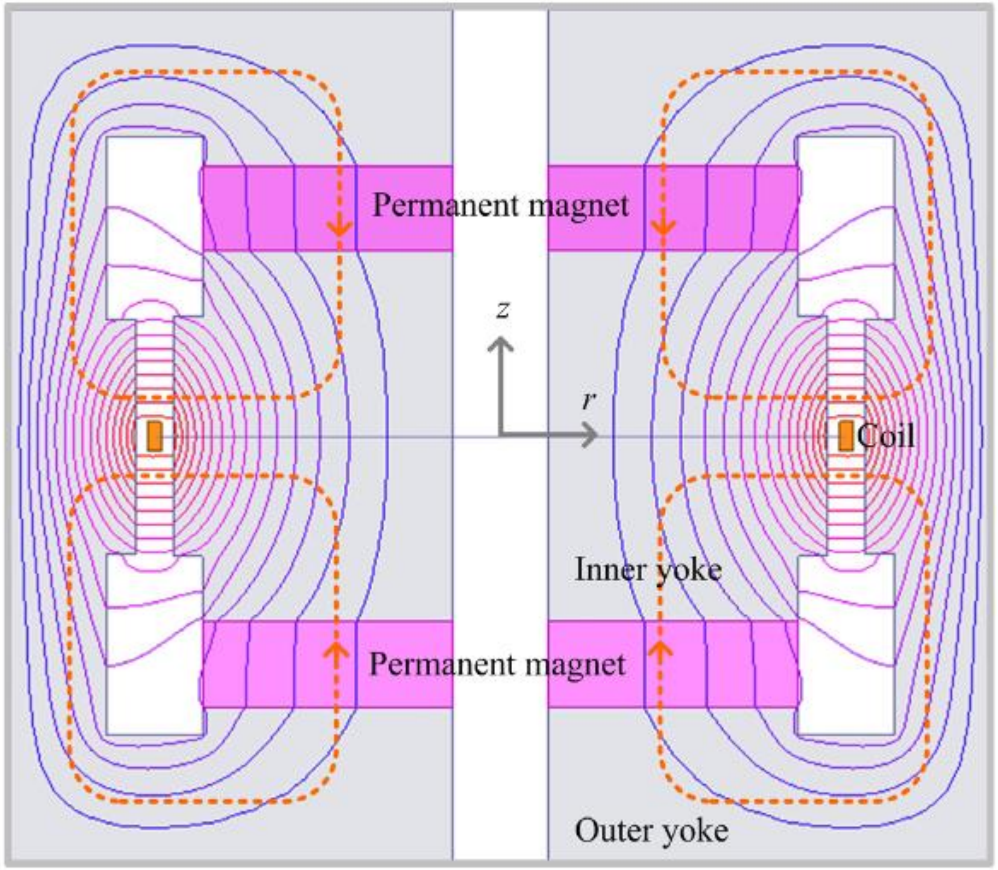
KB magnetic effects: Coil self inductance

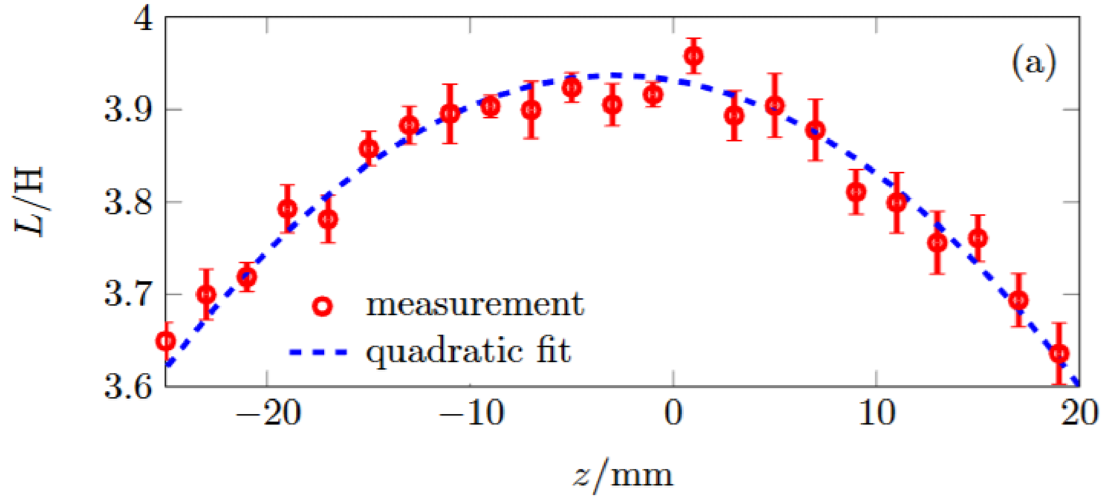
$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

$$E = \frac{L}{2}I_1^2 + \frac{L}{2}I_2^2 + MI_1I_2$$

$$\Delta F = \frac{\partial E}{\partial z} = \frac{I^2}{2}\frac{\partial L}{\partial z}$$

$$\Delta (Bl)_w = \frac{\Delta F}{I} = \frac{I}{2}\frac{\partial L}{\partial z}$$

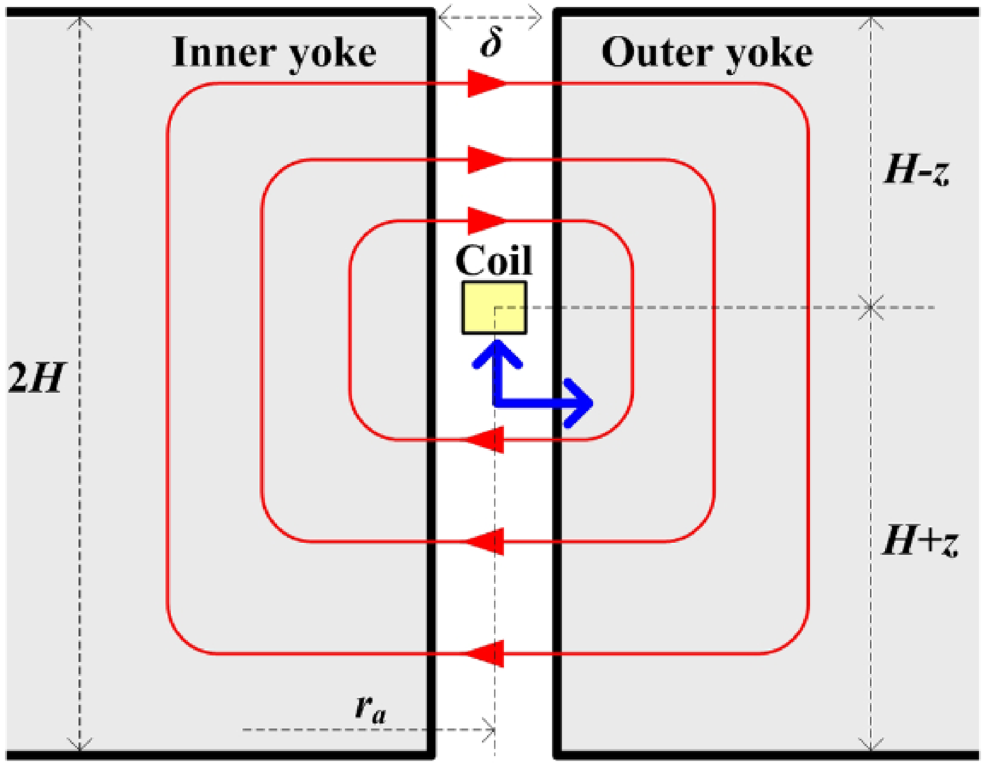




Li S et al Metrologia 55 (2018) 75–83

KB magnetic effects: *Coil self inductance*

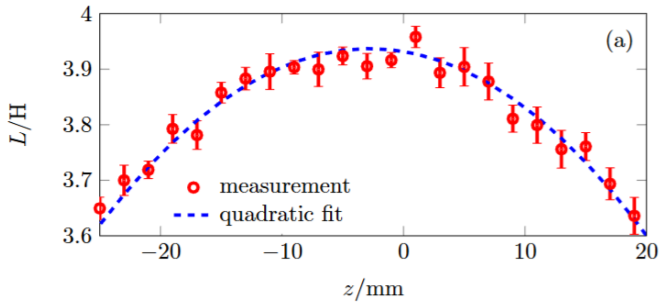
$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

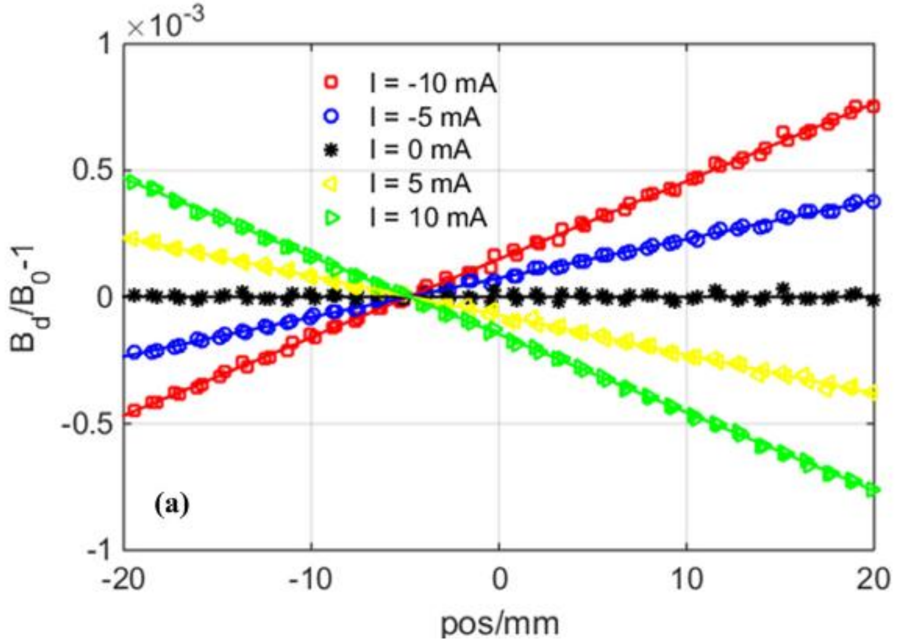


$$NI = \left(\frac{\delta}{\mu_0 2\pi r_a (H-z)} + \frac{\delta}{\mu_0 2\pi r_a (H+z)}\right)\phi$$

$$L = N\phi/I$$

$$L = \frac{\pi \mu_0 N^2 r_a (H^2 - z^2)}{H\delta}$$





Li S et al Metrologia 54 (2017) 775–783

KB magnetic effects: *Coil self inductance*

BIPM

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

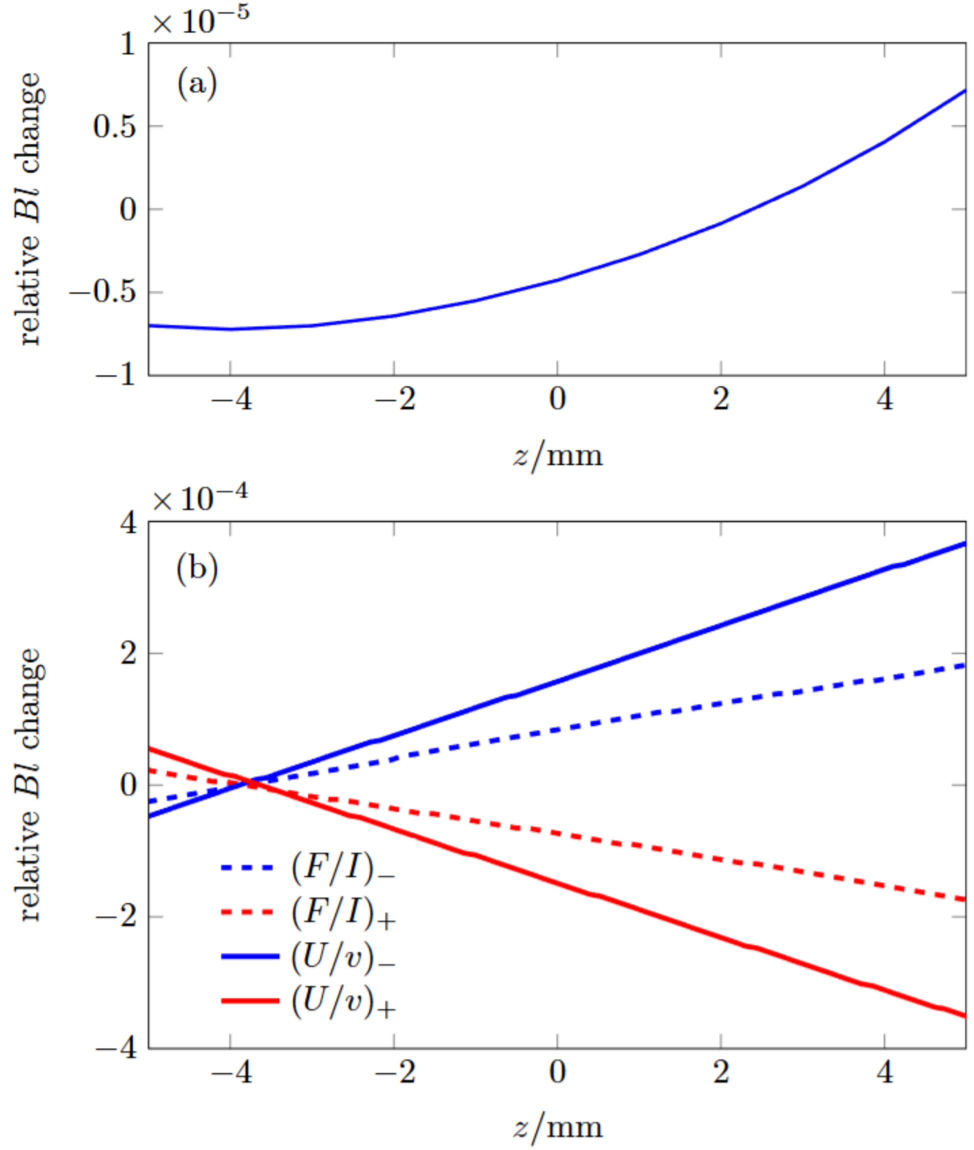
$$\begin{bmatrix}\Delta U_1 \\ \Delta U_2\end{bmatrix} = \begin{bmatrix}U_1 - Blv \\ U_2 - Blv\end{bmatrix}$$

$$= \begin{bmatrix}L_1 & M \\ M & L_2\end{bmatrix}\begin{bmatrix}\partial I_1/\partial t \\ \partial I_2/\partial t\end{bmatrix} + \begin{bmatrix}\partial L_1/\partial t & \partial M/\partial t \\ \partial M/\partial t & \partial L_2/\partial t\end{bmatrix}\begin{bmatrix}I_1 \\ I_2\end{bmatrix}$$

$$\Delta U = \Delta U_2 = I\frac{\partial M}{\partial t} = I\frac{\partial M}{\partial z}\frac{\partial z}{\partial t} = Iv\frac{\partial L}{\partial z}$$

$$\Delta (Bl)_v = \frac{\Delta U}{v} = I\frac{\partial L}{\partial z}.$$

$$\Delta (Bl)_v = 2\Delta (Bl)_w$$



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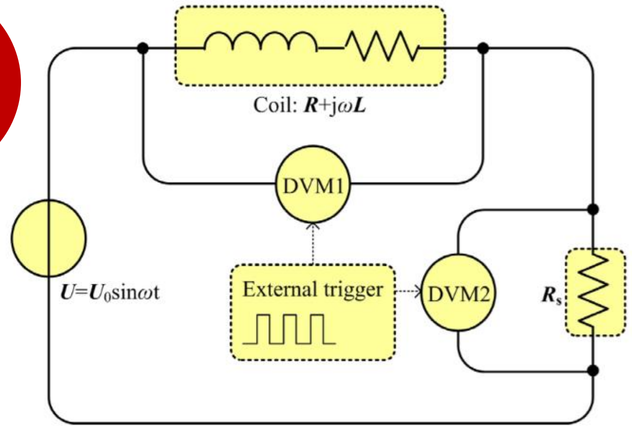
KB magnetic effects: *Coil self inductance*

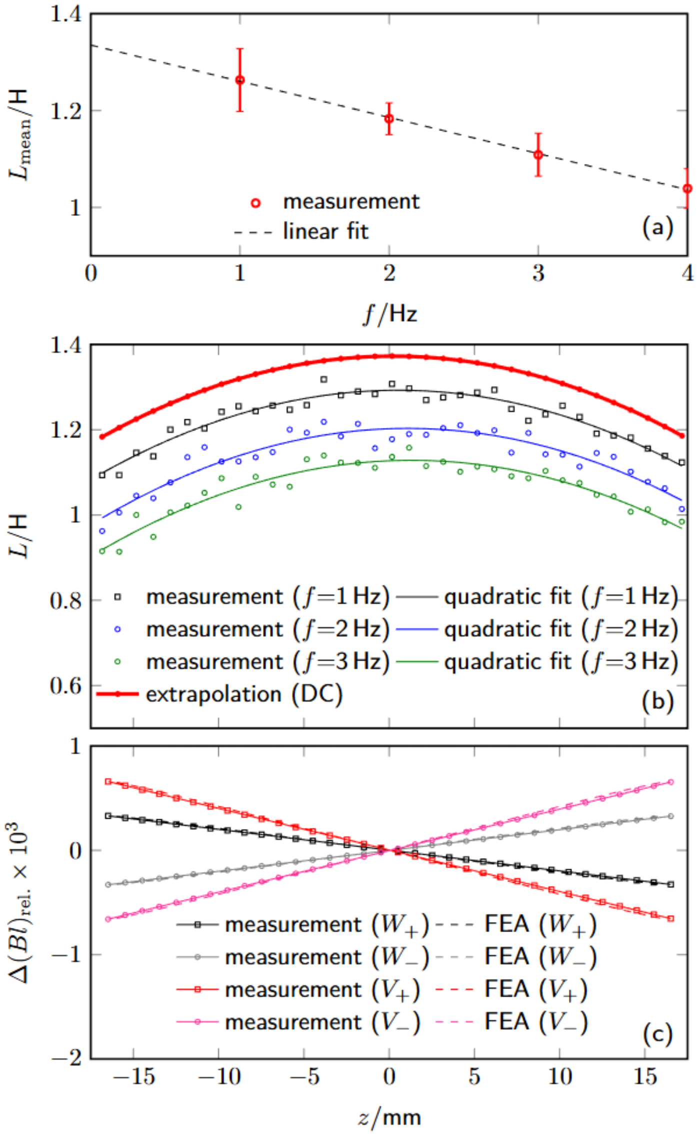
$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

A

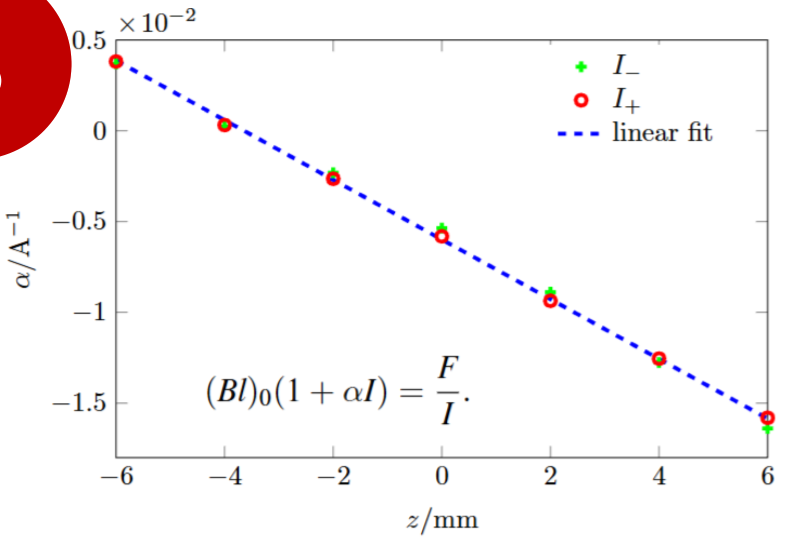


$$\frac{R_s^2}{R_s^2 + (\omega L)^2} = \left(\frac{V_R}{V_L}\right)^2,$$

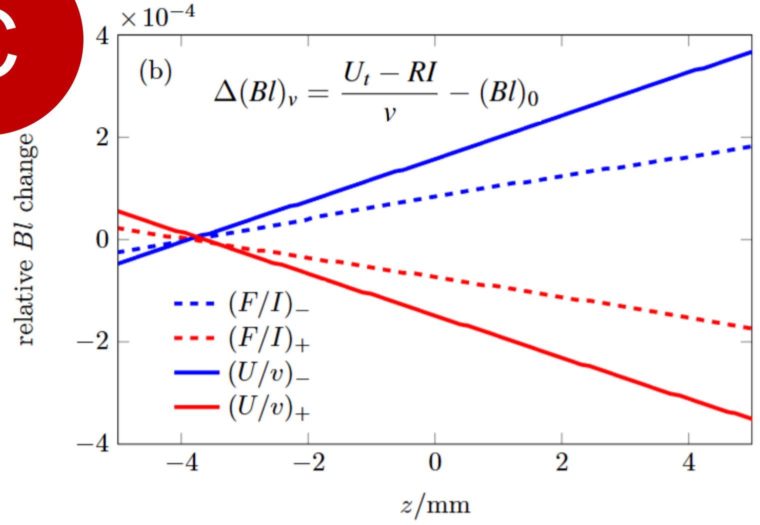
$$\frac{\omega L}{R_L} = \tan(\phi_L - \phi_R),$$



B



C



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KB magnetic effects: Coil self inductance

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

$$\begin{cases} BlI_+[1 + \alpha(z_+)I_+] = mg - m_c g - m_e g \\ BlI_-[1 + \alpha(z_-)I_-] = -m_c g - m_e g \end{cases}$$

$$(Bl)_w = \frac{mg}{I_+ - I_-} = Bl\left[1 + \frac{\alpha(z_+)I_+^2 - \alpha(z_-)I_-^2}{I_+ - I_-}\right]$$

$$\varsigma \approx \frac{k(z_+ - z_-)(I_+ - I_-)}{4} + k\left(\frac{z_+ + z_-}{2} - z_0\right)(I_+ + I_-).$$

Linear current effect, ~10ppb/µm for the BIPM system

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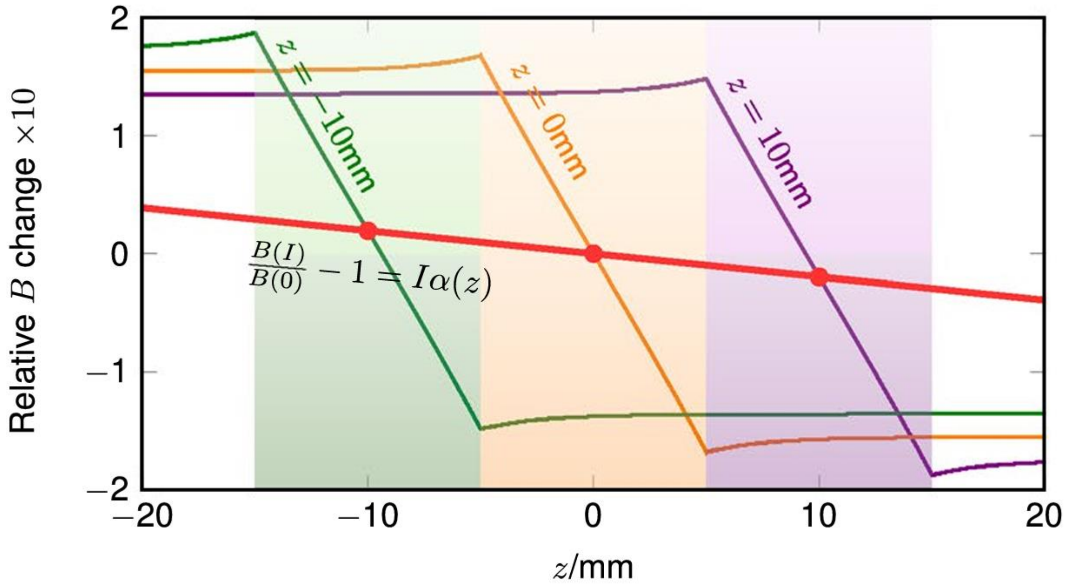
KB magnetic effects: *Diamagnetic effect*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

$$F_\mathrm{d} = \frac{\int \chi \,\mathrm{d}V}{\mu_0} \frac{1}{2} \frac{\partial}{\partial z}(B+b)^2,$$



Positive current, negative field gradient
Negative current, positive field gradient!

The effect is up to 1ppm!

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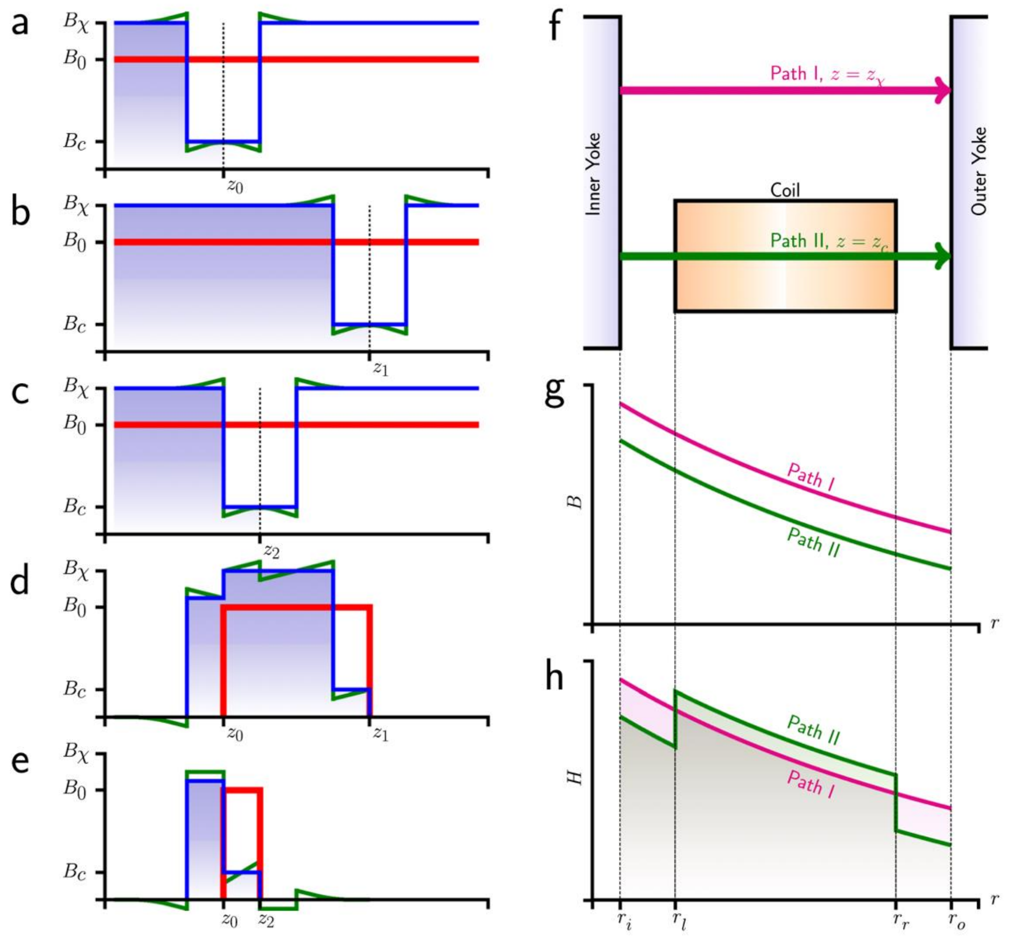
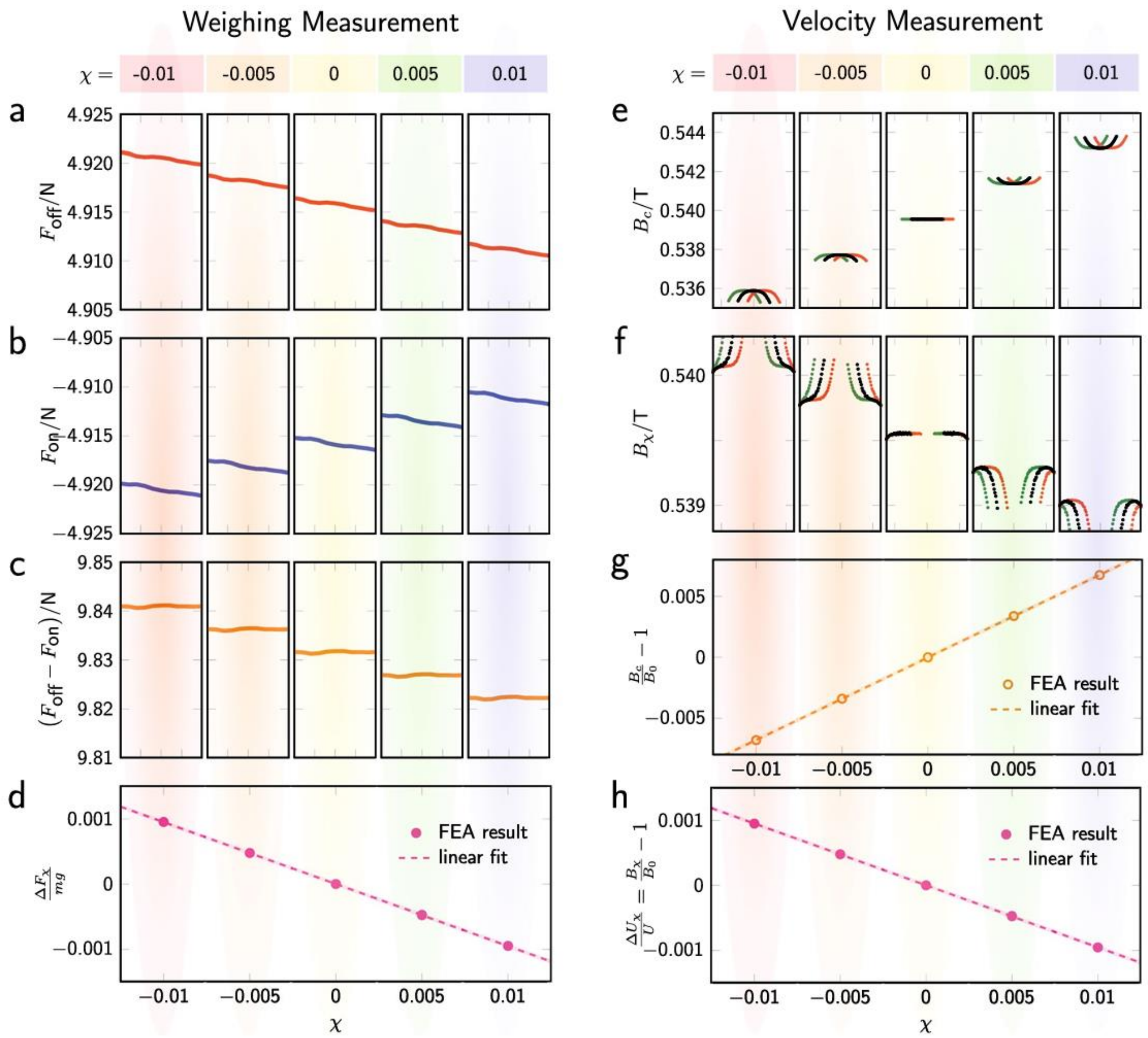
KB magnetic effects: Diamagnetic effect

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$



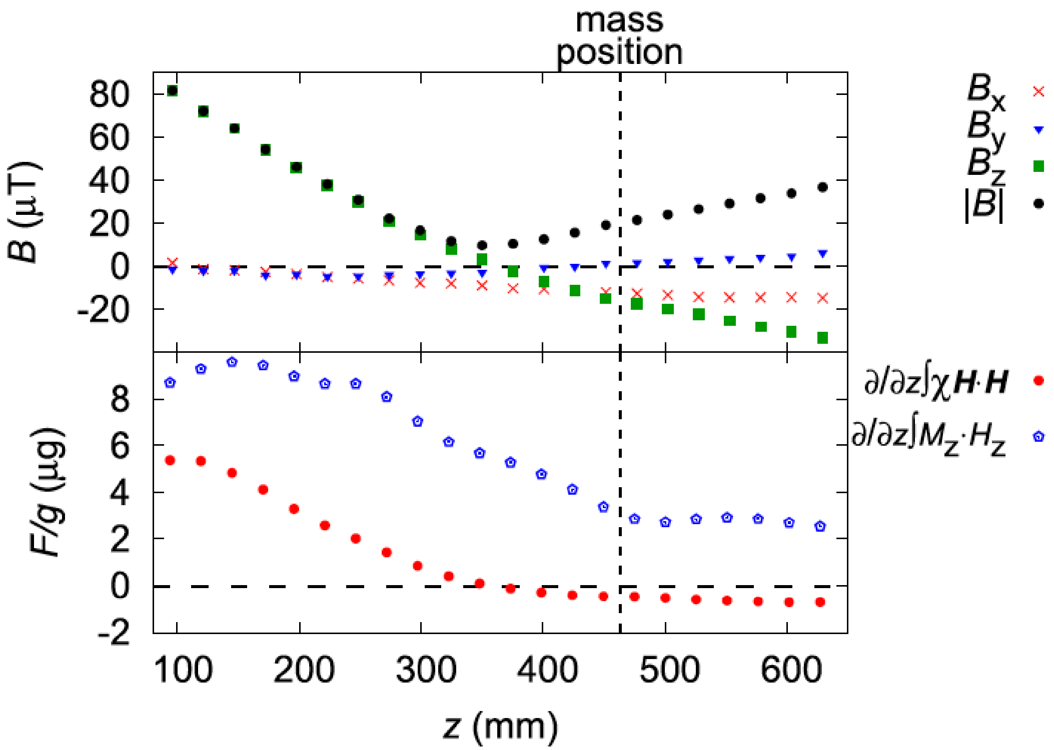


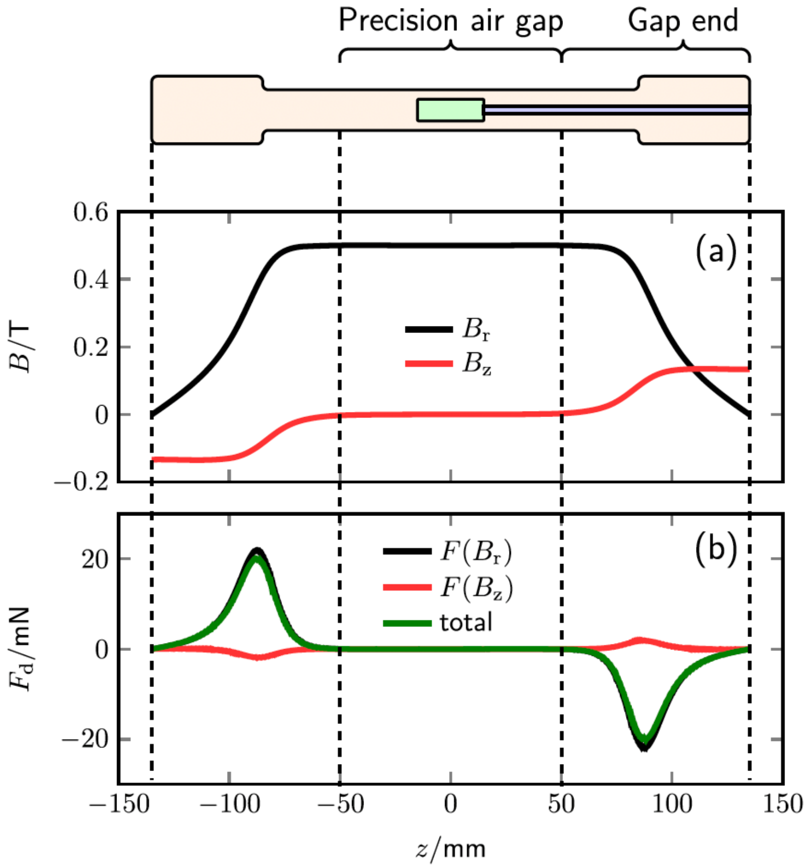
Li S et al Scientific Reports (2021) 11:1048

KB magnetic effects: *magnetization effect*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$

$$F_z = -\frac{\mu_0}{2}\frac{\partial}{\partial z}\int \chi \mathbf{H}\cdot\mathbf{H}dV - \mu_0\frac{\partial}{\partial z}\int \mathbf{M}\cdot\mathbf{H}dV.$$



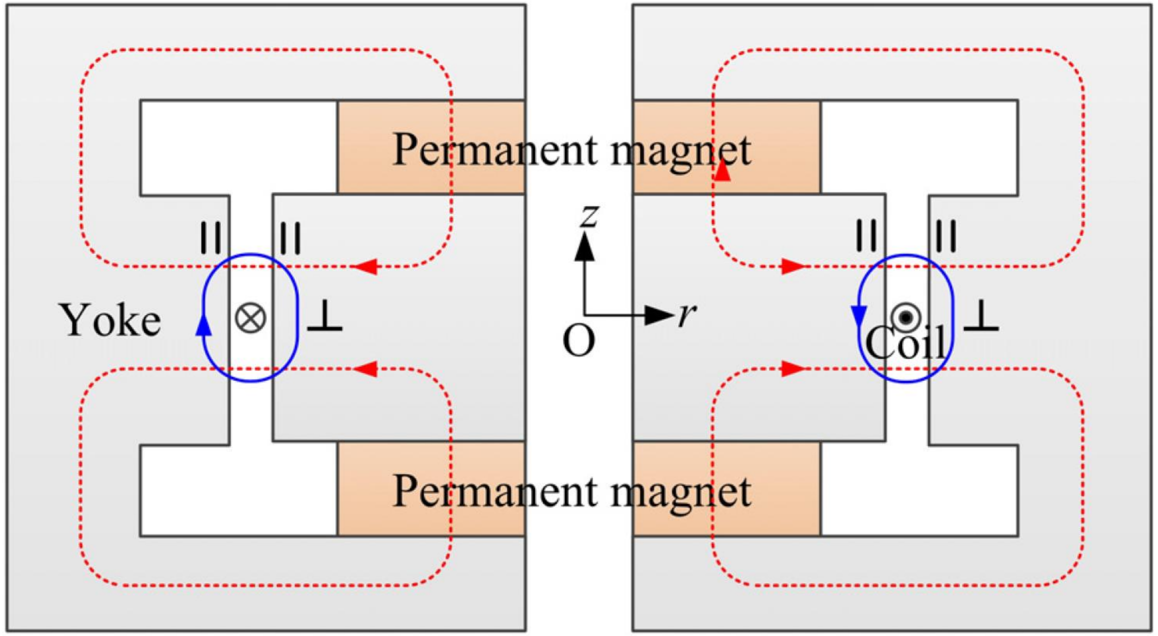


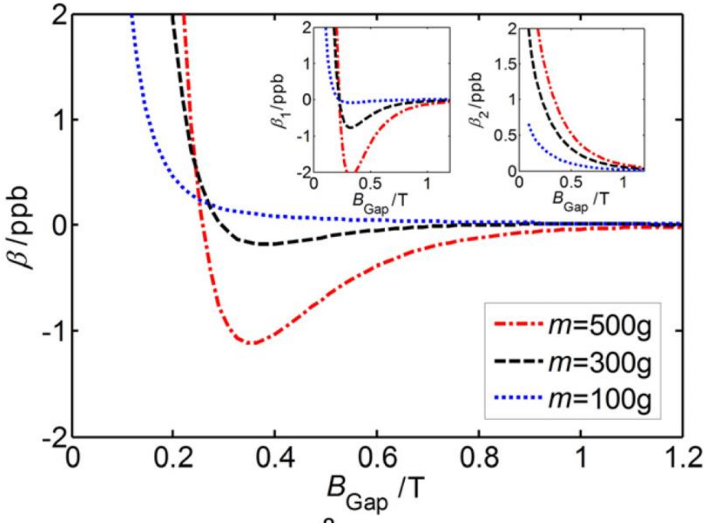
Seifert F et al 2014 IEEE TIM 63 3027

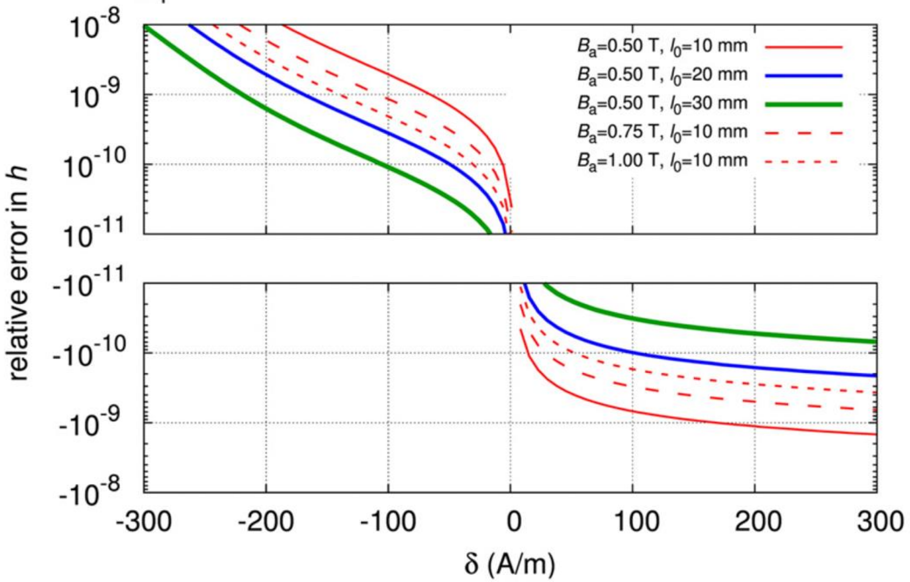
Li S, Schlamminger S 2022 Metrologia 59 022001 (30pp)

KB magnetic effects: *Nonlinear current effects*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$







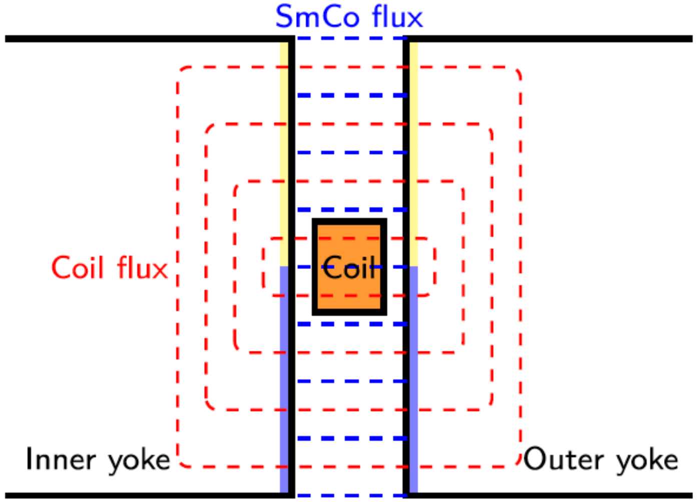
Yoke nonlinearity, considering the main BH curve. The effect is negligible.

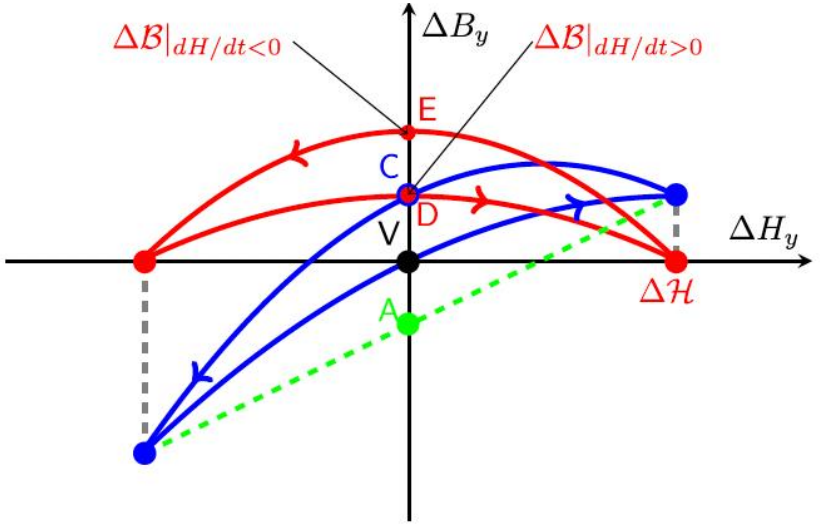
Li S et al Metrologia 50 (2013) 482–489 Li S et al Metrologia 51 (2014) 394–401

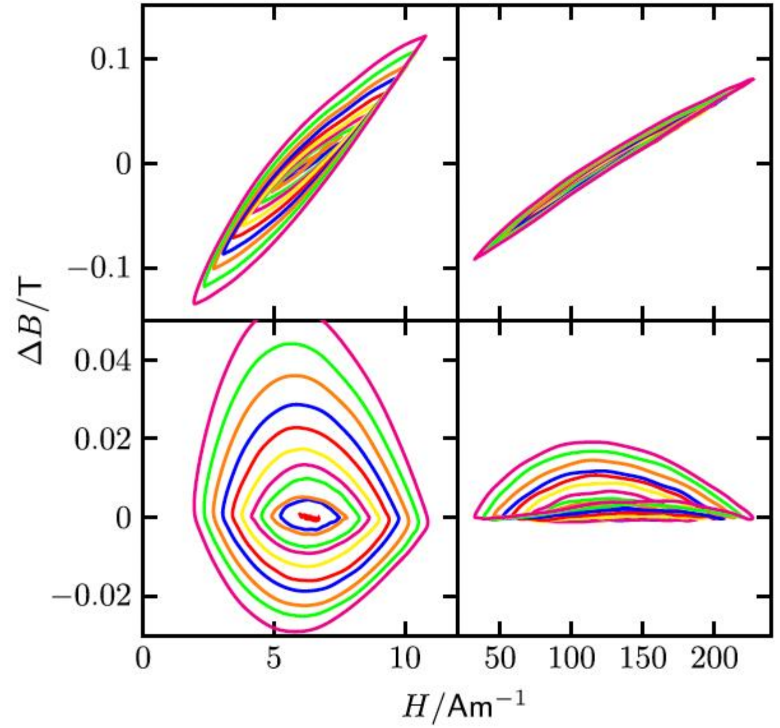
KB magnetic effects: *Nonlinear current effects*

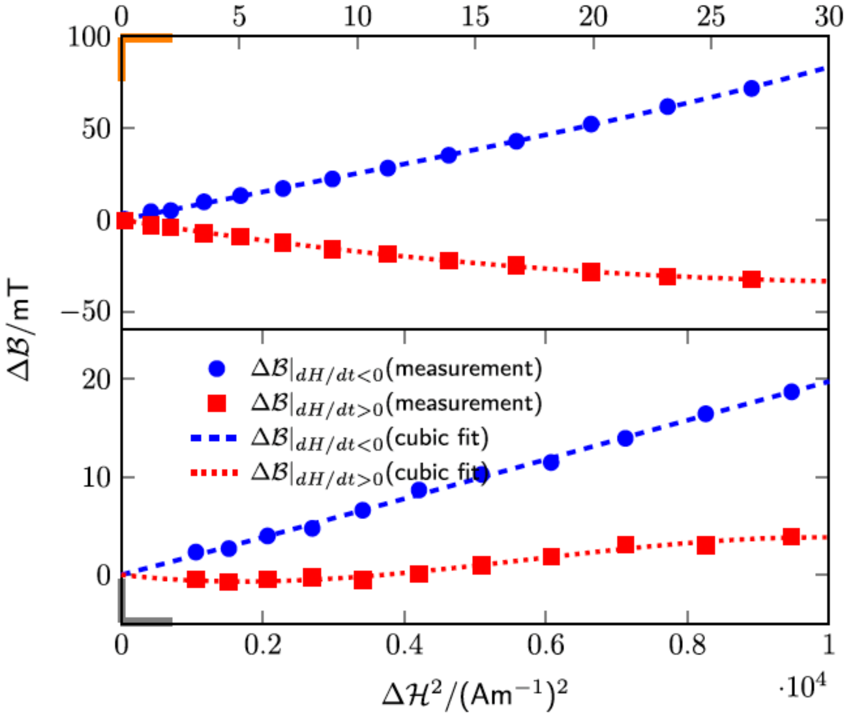
BIPM

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$









BIPM system

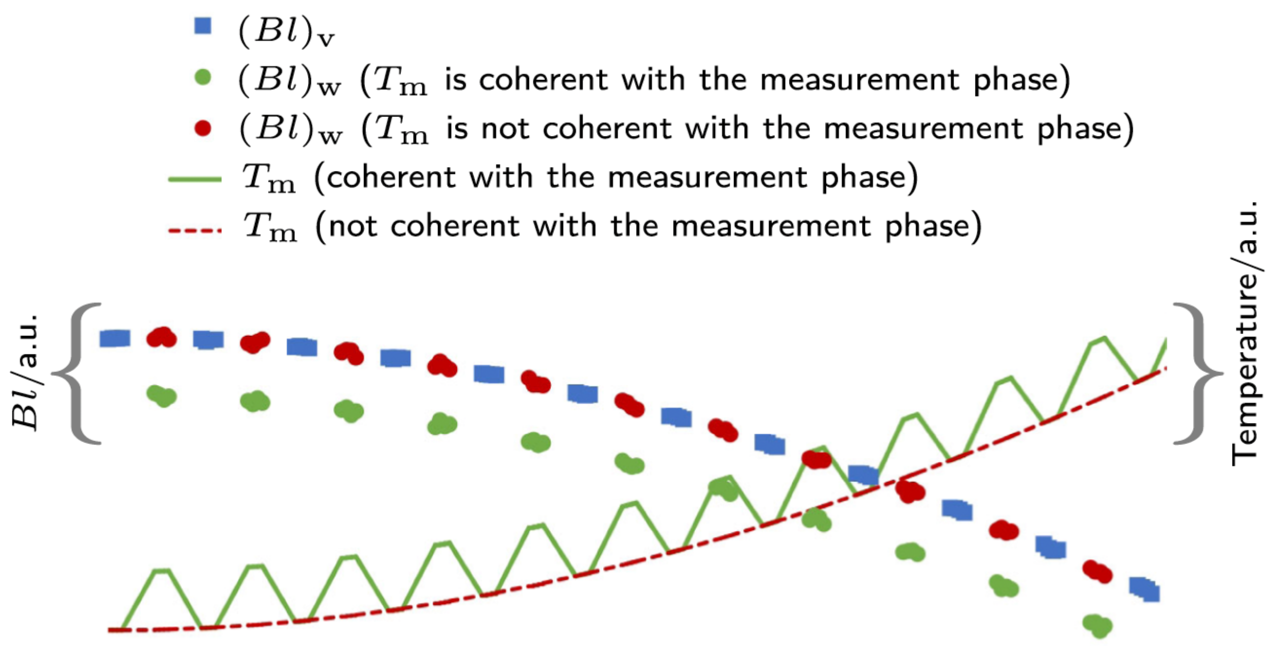
Yoke no heat treatment: (-16.8±2.8)ppb

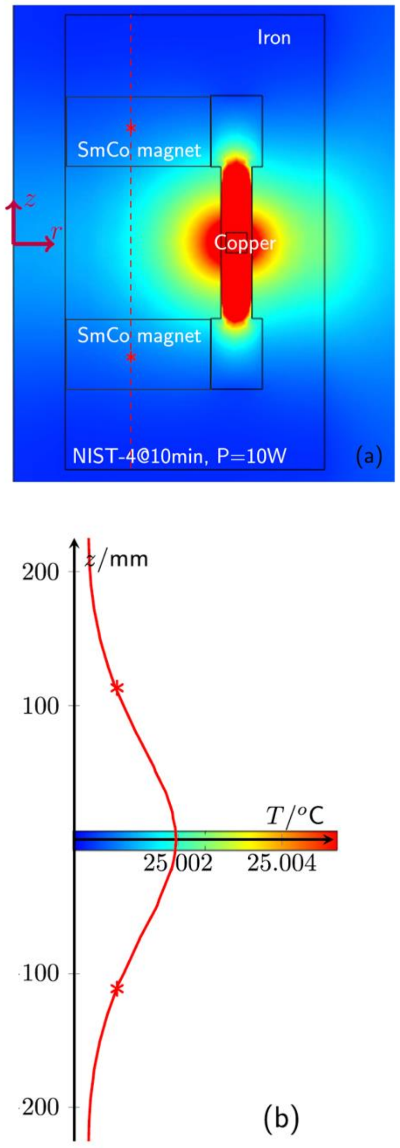
Yoke with heat treatment: (-21±4.8)ppb

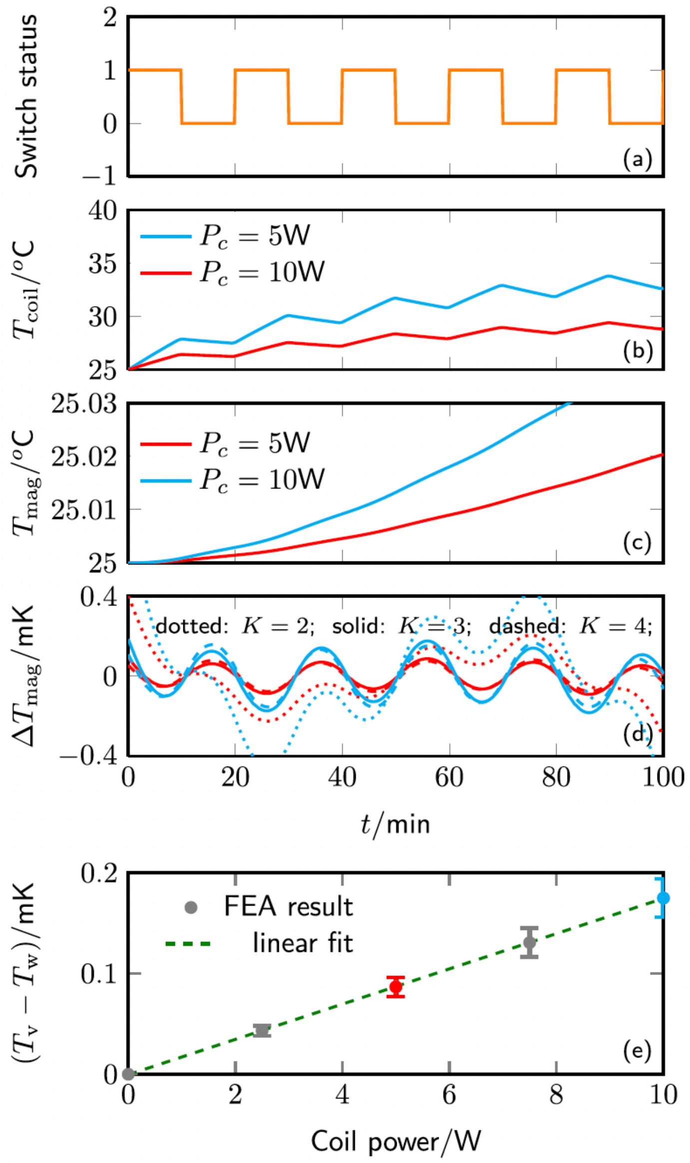
Li S et al IEEE TIM 2020 69 5717-5724

KB magnetic effects: *Thermal-magnetic effect*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$





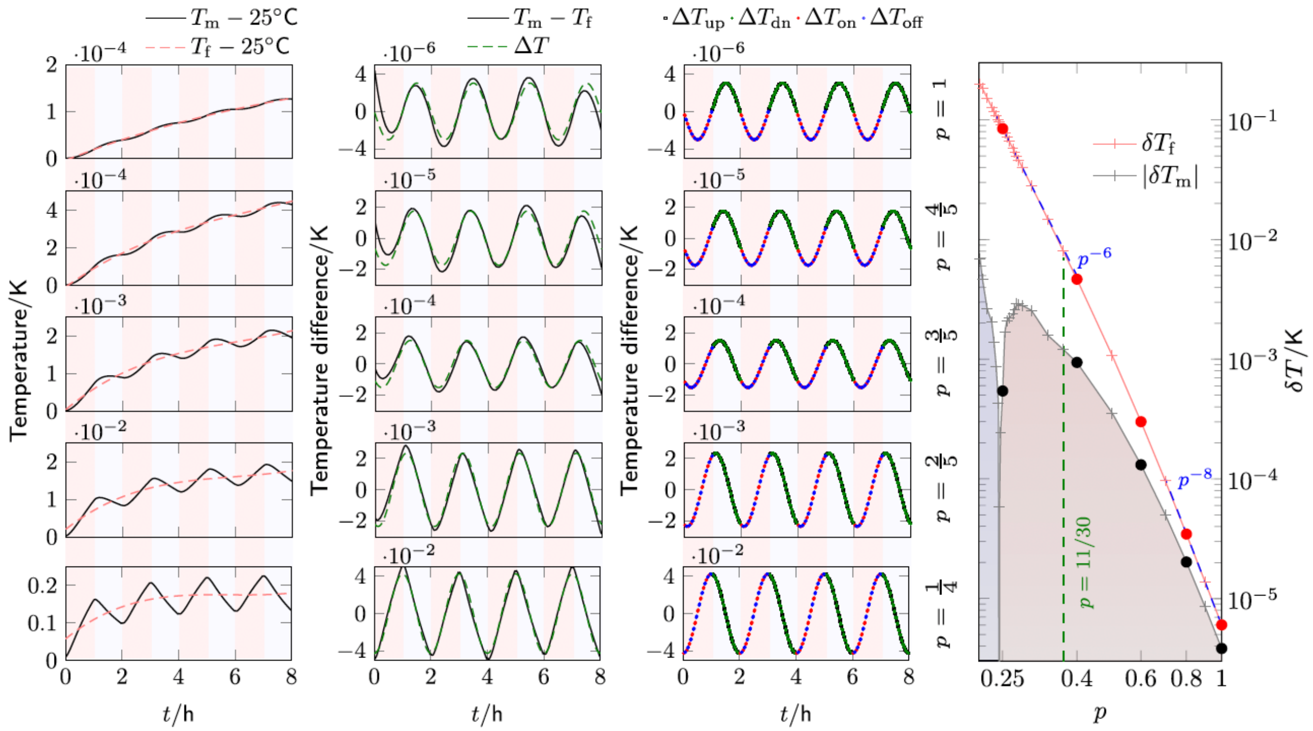


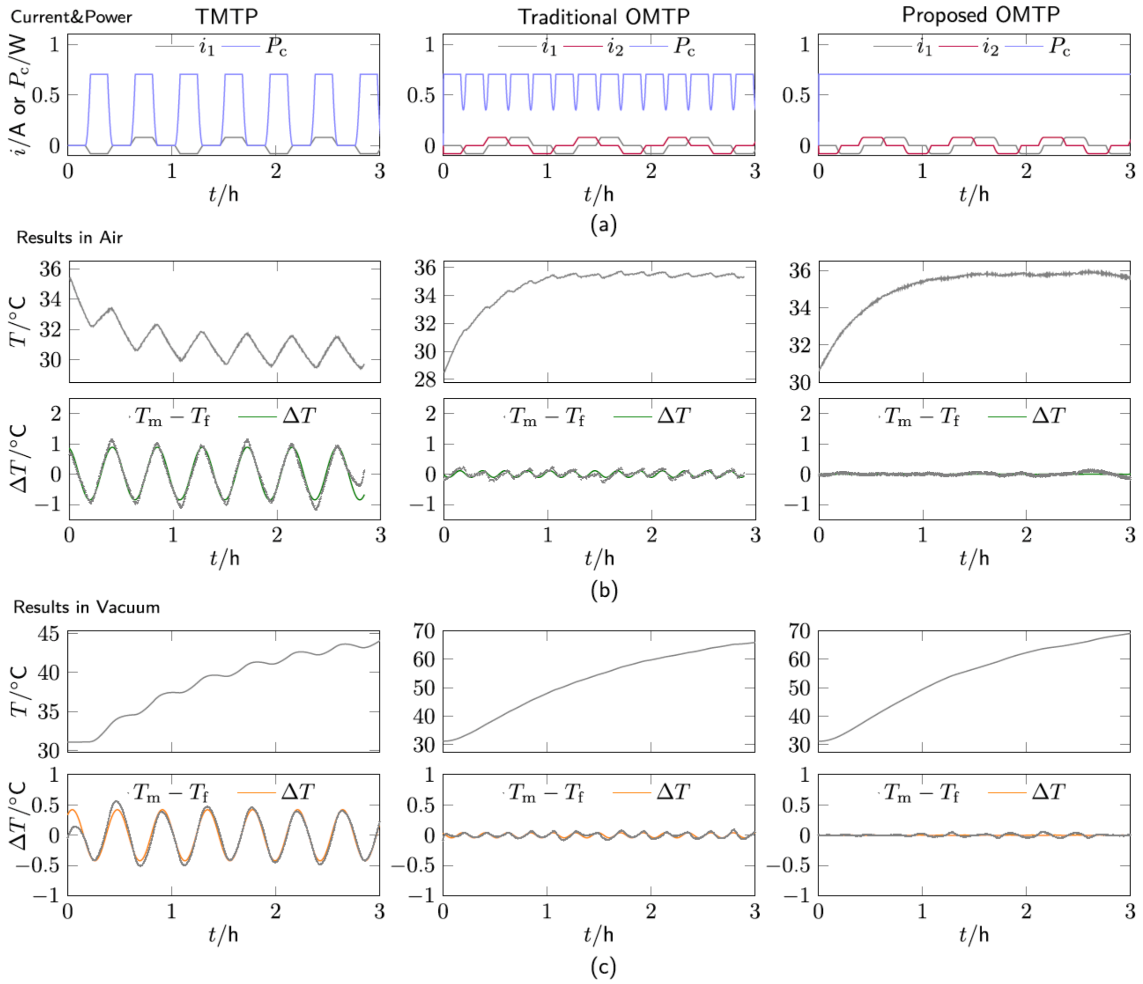
Effect is found proportional to p^{-8}

Li S, Schlamminger S 2022 IEEE TIM 71: 1502409

KB magnetic effects: *Thermal-magnetic effect*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$





Experimental verification ~

One mode scheme can reduce the effect to 10%, and a further sin/cos current ramping to ~1%.

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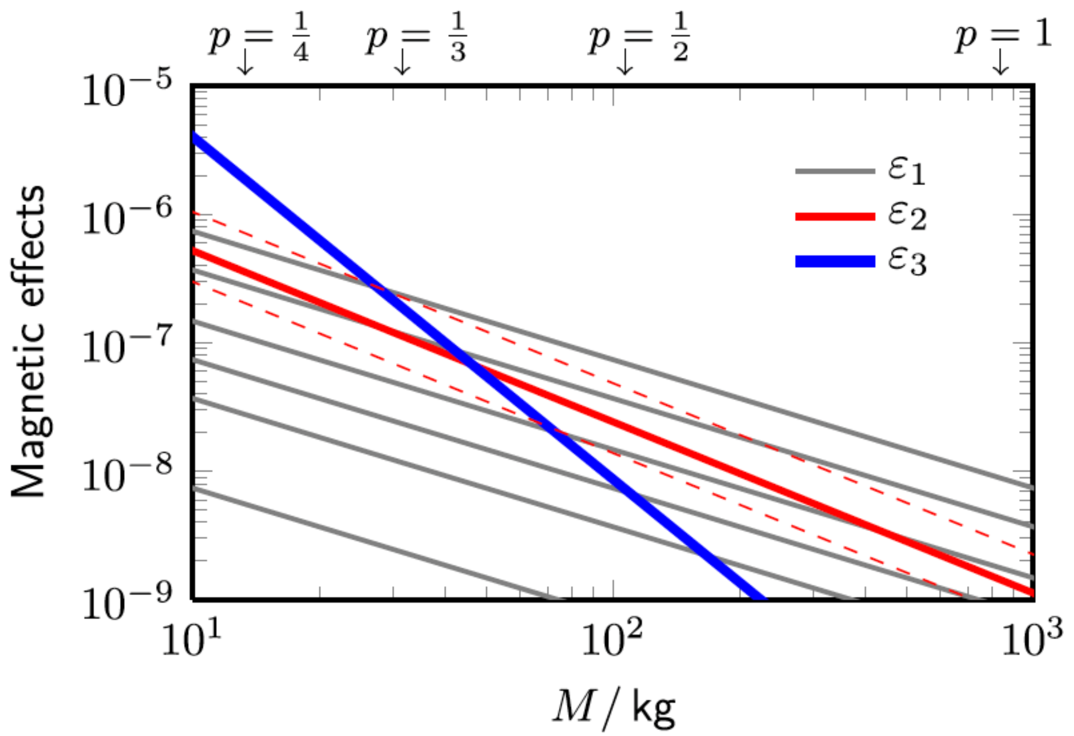
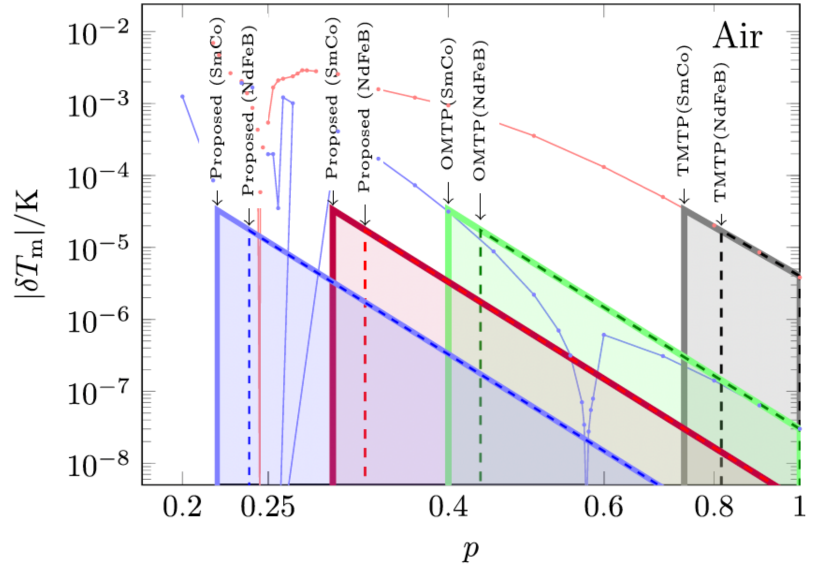
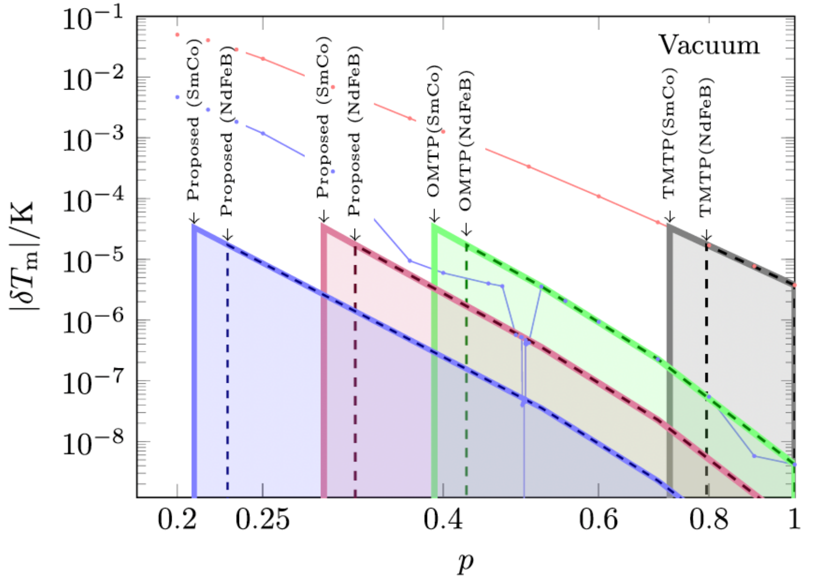
KB magnetic effects: *Thermal-magnetic effect*

$$(Bl)_w = (Bl)_v(1 + \alpha I + \beta I^2)$$







Set a size boundary for KB magnets!

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Outlines

1. Magnetic basics in KB experiments
2. A Brief history KB magnet-coil designs
3. How to design a KB magnet system
4. Evaluation performance of a KB magnet
5. Systematic effects and how to reduce
6. Summary & outlook

6 Summary & outlook

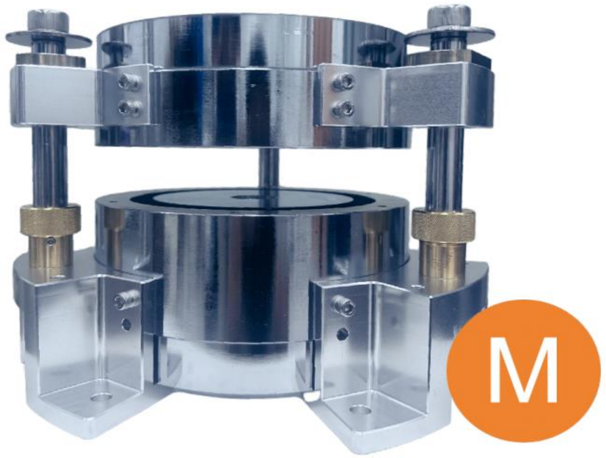
6.1 Tabletop considerations

6.2 Open-hardware magnet system

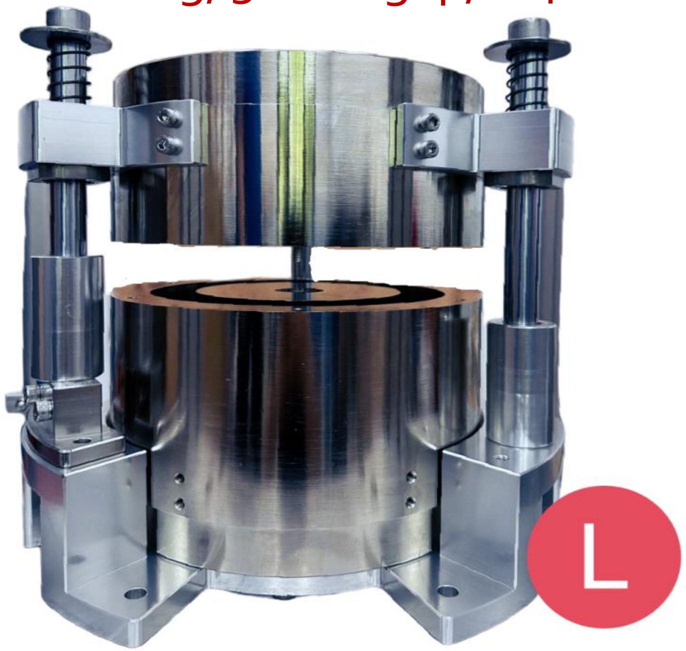
6.3 Future trends

20kg, 10mm gap, 0.6T

40kg, 15mm gap, 0.6T



60kg, 30mm gap, 0.4T



Thanks!

Thank you.

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