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Cours/Lecture Series

1982-1983 ACADEMIC TRAINING PROGRAMME

Title "Permanent magnet technology"

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Dates October 21 & 22, 1982

Time 10h30 to 12h30

Place Auditorium

Abstract

Theory of permanent magnet state.

Permanent magnet materials, manufacturing processes and properties : hard ferrites, AlNiCo, rare earth metal-cobalt (RECo), other.

Design of permanent magnet circuits : conventional, analytical and numerical methods.

Typical permanent magnet circuits and applications, with emphasis on RECo-devices in particle optics.

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The permanent magnet circuit

1. Materials

1.1. Permanent magnet materials

1.1.1. Theory of permanent magnet state

1.1.2. Manufacturing and properties
- AlNiCo
- Hard ferrite
- RE-Co
- Other

1.1.3 Magnetizing

1.1.4. Influences on permanent magnets
- Magnetic fields
- Temperature

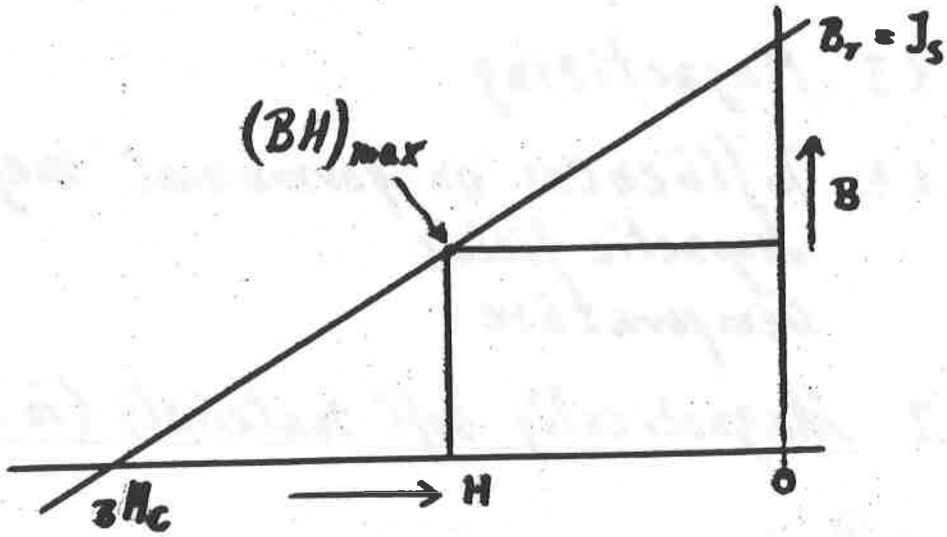
1.2. Magnetically soft materials (in PM circuit)

2. Design

3. Applications

The ideal permanent magnet.

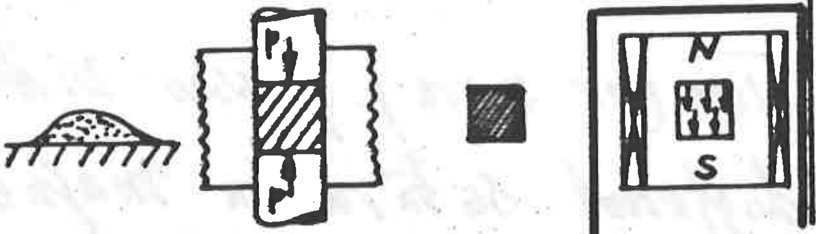
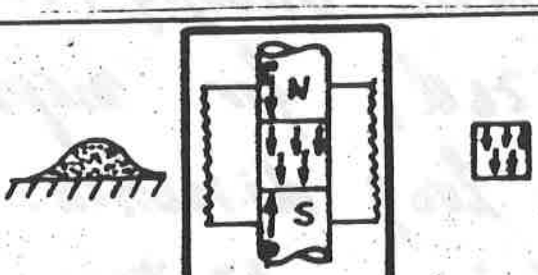
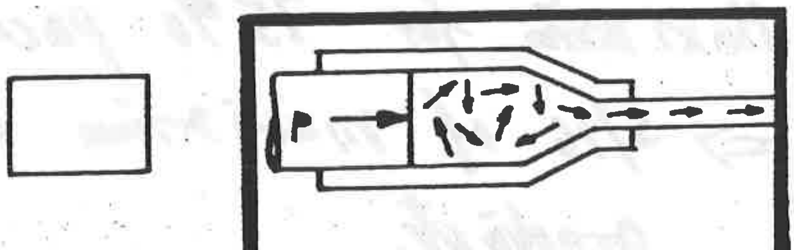
1. high B_r → high J_s / Primary properties
2. high ${}_J H_c$ → high anisotropy / no moving Bloch-walls
3. $\mu_{rev} = 1$, $B_r = J_s$ → same anisotropy direction for the whole magnet



Theoretical maximum: $J_s^2 / 4\mu_0$

$J_s = 2{,}4\,T \longrightarrow (BH)_{max} = 1200 \frac{kJ}{m^3}$

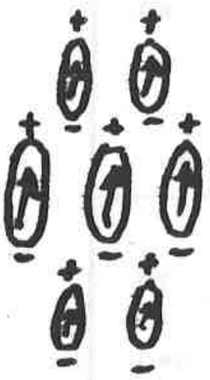
| crystal anisotropy
| shape "

Material	Herstellverfahren für anisotrope Dauermagnete	Energieinhalt kJ/m^3
AlNiCo (KOERZIT)	 Pulver → Pressen → Sintern → Wärmebehandlung im Magnetf.	40
Hartferrit (KOEROX) $SECo_5$ (KOERMAX) $SE_2(Co,M)_{17}$	 Pulver → Pressen im Magnetfeld → Sintern	30 160 220
MnAlC	 Gußblock → Warmfließpressen	50

1. <u>Crystal anisotropy.</u>

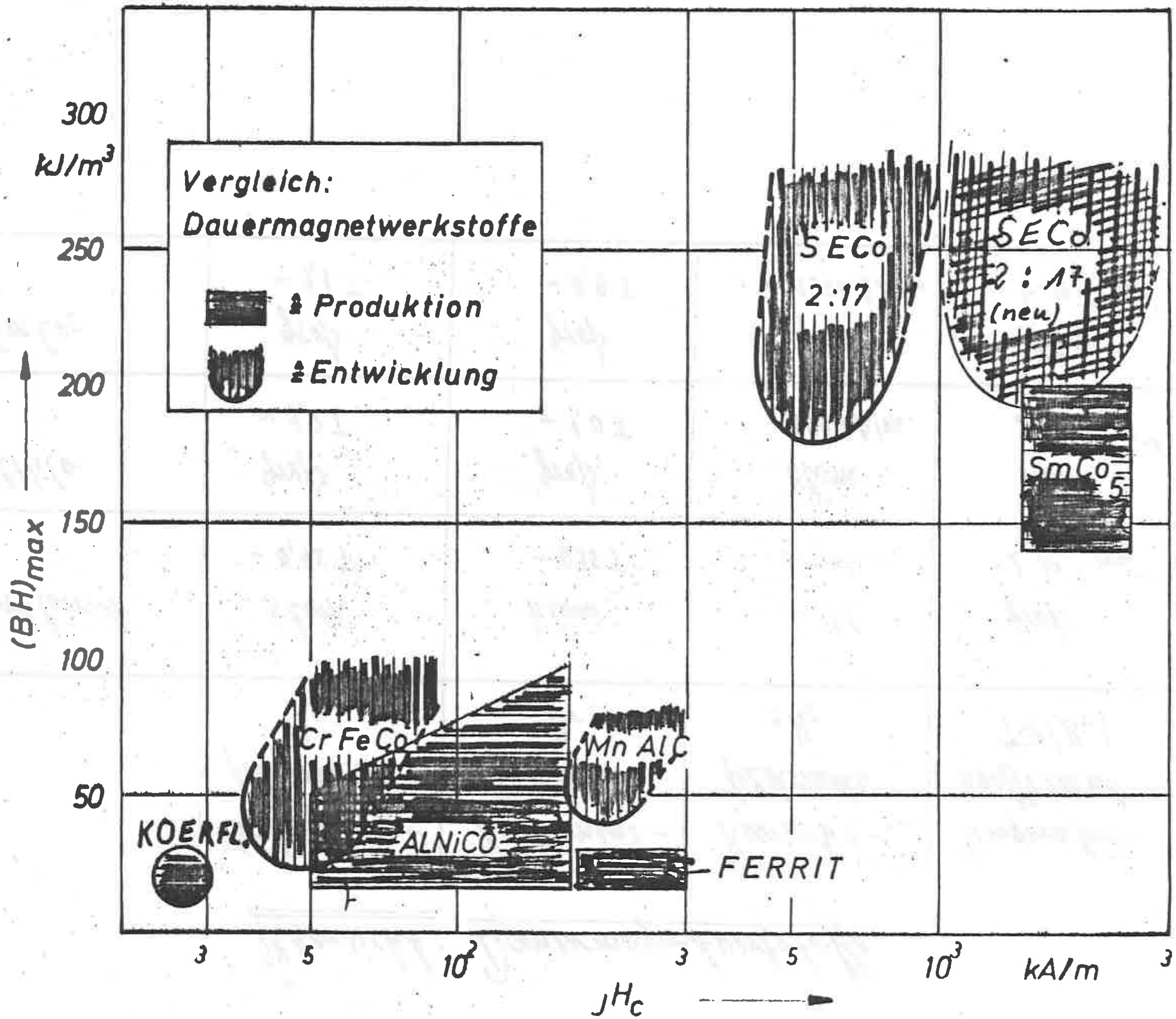
In each crystallite magnetization fixed to some directions.

2. <u>Shape anisotropy</u>



Two (or more) phases with different saturation magnetization. Magnetostatic energy (ME) is minimized, for magnetization in the long direction.
By packing reduction of ME.
Maximum for 75% packing fraction.
⇒ 5/16 of maximum energy product.

3. <u>Strain anisotropy</u> (unimportant)



Vergleich:
Dauermagnetwerkstoffe
≙ Produktion
≙ Entwicklung
300
kJ/m³
250
200
150
100
50
(BH)max
SECo
2:17
SECo
2:17
(neu)
SmCo5
Cr Fe Co
Mn Al C
KOERFL.
ALNiCO
FERRIT
3
5
10²
3
5
10³
kA/m
3
JHc

5

Übersicht: Dauermagnetwerkstoffe

	Sättigungspolarisation J_s	Remanenzflußdichte B_r	Koerzitivfeldstärke $_JH_C$	Temperaturkoeffizient $TK(B_r)$
Hartferrit	klein ~ 0,45 T	klein ~ 0,35 T	mittel ~ 300 kA/m	groß $2 \cdot 10^{-3}$ grd^{-1}
AlNiCo	groß ~ 1,2 T	groß ~ 1,0 T	klein ~ 100 kA/m	klein $2 \cdot 10^{-4}$ grd^{-1}
$SmCo_5$	groß ~ 1,1 T	groß ~ 0,9 T	groß ~ 1500 kA/m	klein $4 \cdot 10^{-4}$ grd^{-1}

KOERMAX

Dauermagnetwerkstoff aus Seltenerdmetall und Kobalt

Vorbemerkung

KOERMAX ist ein pulvermetallurgisch hergestellter, anisotroper Dauermagnetwerkstoff aus Seltenerdmetallen und Kobalt mit ausgezeichneten magnetischen Eigenschaften. Er übertrifft bei hoher Sättigungspolarisation alle bisher eingesetzten Dauermagnetwerkstoffe im maximalen Energieprodukt und in der Koerzitivfeldstärke und bildet daher die sinnvolle Ergänzung der bekannten KRUPP Dauermagnetwerkstoffe **KOERZIT**, **KOEROX** und **KOERFLEX**. KRUPP WIDIA liefert die Sorten **KOERMAX 130** und **KOERMAX 160** mit typischen Werten des maximalen Energieproduktes von 130 und 160 kJ/m³. Über den Einsatz der Sorten entscheiden die magnetischen Anforderungen sowie Größe und Form der Magnete.

Magnetische Kennwerte

In der Tabelle 1 sind die magnetischen Werte der beiden Sorten in ihren typischen Streubreiten wiedergegeben. **KOERMAX 130** entspricht der einzigen in der DIN 17410 aufgeführten Seltenerdmetall-Kobalt-Sorte SECo 112/100, bei **KOERMAX 160** wurde zur weiteren Kennzeichnung der Kurzname in Anlehnung an DIN 17410 gewählt. In Bild 1 werden typische Entmagnetisierungskurven von **KOERMAX 130** und **KOERMAX 160**, der AlNiCo-Legierung **KOERZIT 500** und des Hartferritwerkstoffes **KOEROX 330** dargestellt. Die überragenden magnetischen Eigenschaften von **KOERMAX** sind deutlich zu erkennen.

Tabelle 1: Magnetische Kennwerte von **KOERMAX**

Sorte	Kennzeichnung nach DIN 17410	Maximales Energieprodukt $(BH)_{max}$ kJ/m³	Remanenzflußdichte B_r mT	Koerzitivfeldstärke $_BH_c$ kA/m	$_JH_c$ kA/m	Relative permanente Permeabilität μ_p
KOERMAX 130	SECo 112/100	110–140	750–840	520–620	> 1000	≤ 1,1
KOERMAX 160	SECo 140/120	140–180	840–950	580–730	> 1200	≤ 1,1
Zur Umrechnung in die bisher gebräuchlichen Einheiten: 1 kJ/m³ = 0,126 MGOe, 1 mT = 10 G, 1 kA/m = 12,6 Oe						

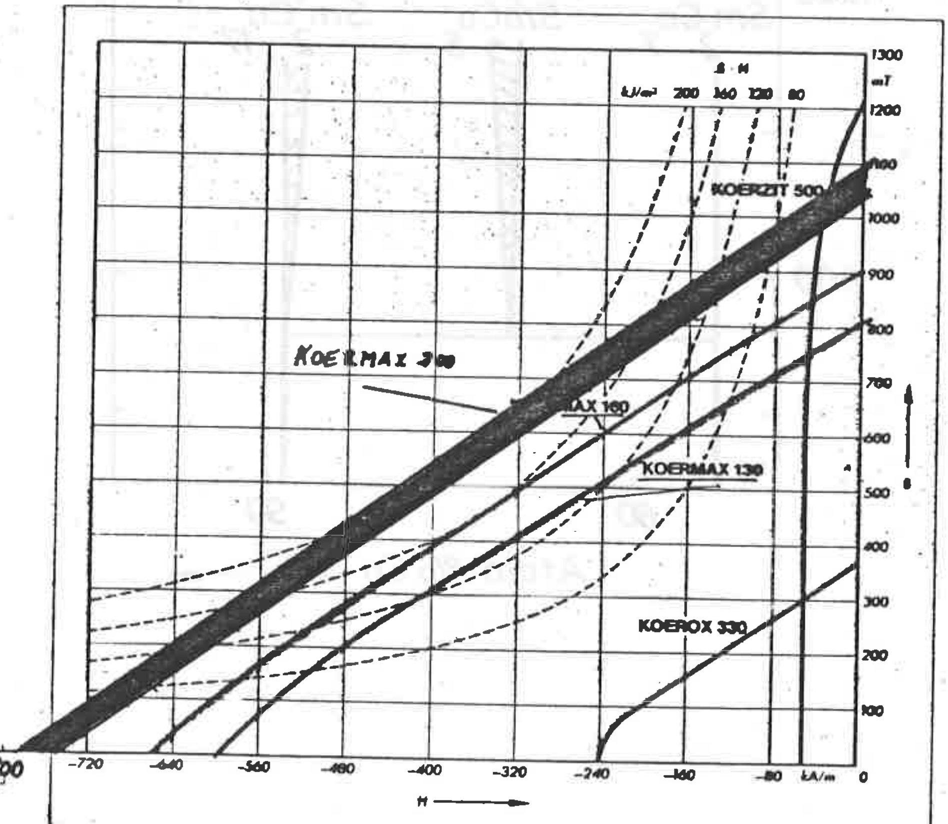
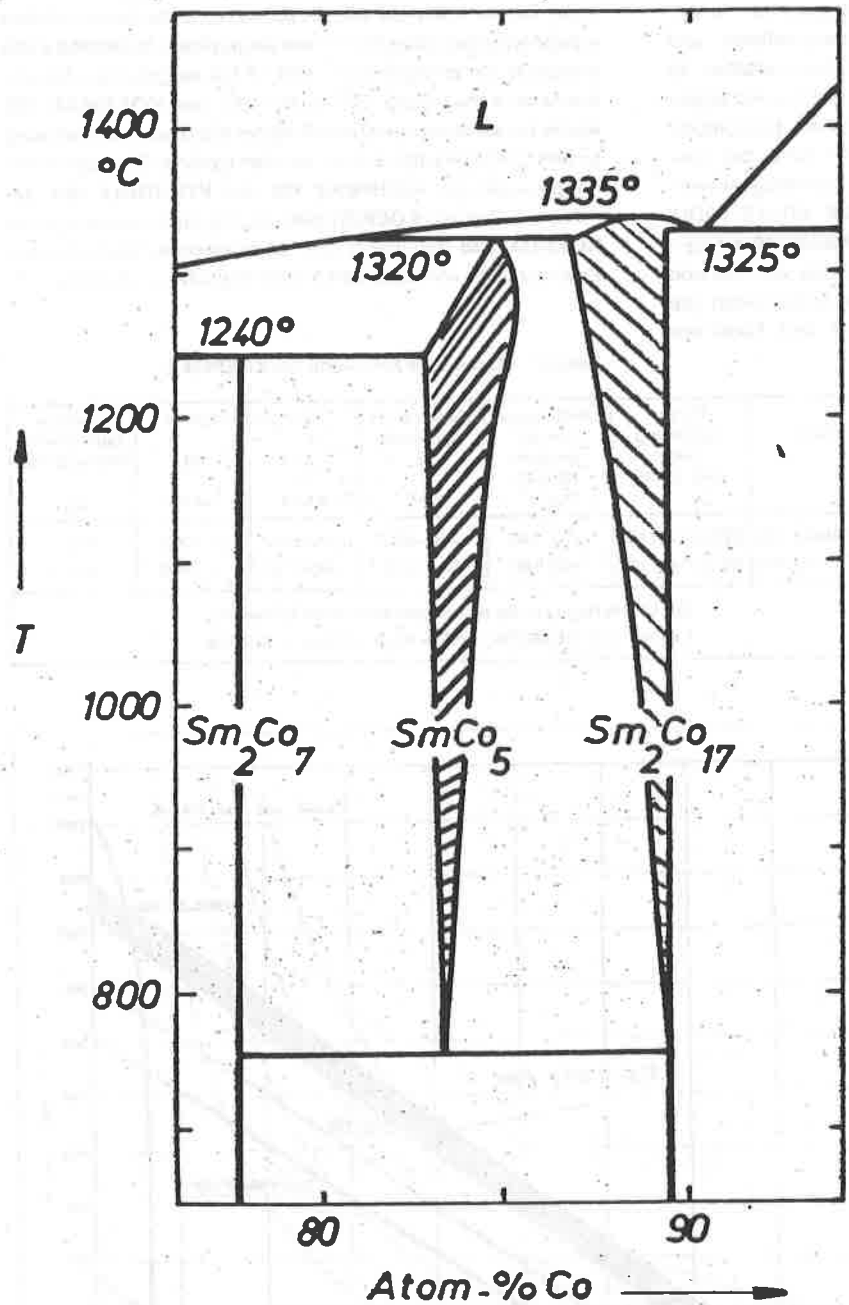
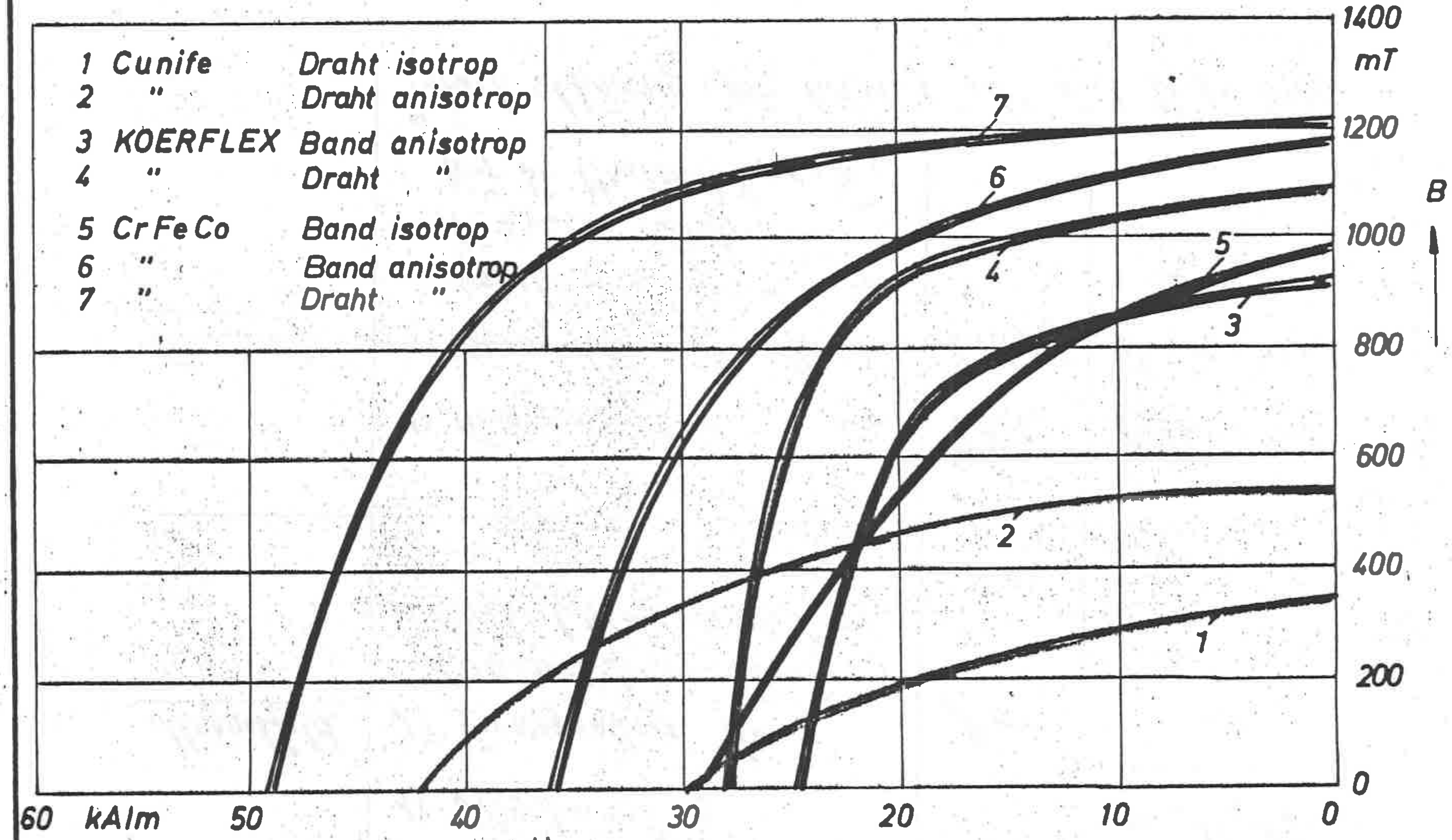


Bild 1: Typische Entmagnetisierungskurven von **KOERMAX 130** und **160**, **KOERZIT 500** und **KOEROX 330**



L
1335°
1320°
1325°
1240°
1400
°C
1200
1000
800
T
Sm2Co7
SmCo5
Sm2Co17
80
90
Atom-% Co



KRUPP WIDIA

Entmagnetisierungskurven verformbarer Dauermagnete

MAGNET-WERKSTOFFE

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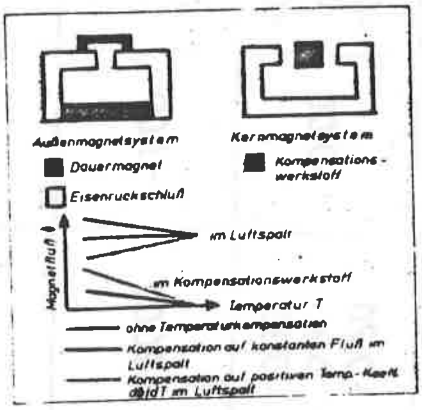
[illegible]

Einflußgröße	irreversibel*) Gegenmaßnahmen	Kenngröße	reversibel Gegenmaßnahmen
Magnetfeld	1) Abschirmung 2) Vorwegnahme der Beanspruchung durch Wechselfeld (Stabilisieren)	μ_{rev}	1) Abschirmung
Temperatur	1) Temperaturbad 2) Vorwegnahme der Beanspruchung durch Temperaturzyklen (Stabilisieren). Nur bis Maximaltemperatur	TK(B_r) TK(H_c)	1) Temperaturbad 2) Temperaturkompensation

*) stark abhängig von Arbeitspunkt und Vorgeschichte



$$\frac{\partial B_M}{\partial T} \cdot A_M = \frac{\partial B_L}{\partial T} \cdot A_L + \frac{\partial B_K}{\partial T} \cdot A_K$$

ES SOLL SEIN: $\frac{\partial B_L}{\partial T} = 0$

DARAUS FOLGT: $\frac{\partial B_M}{\partial T} \cdot A_M = \frac{\partial B_K}{\partial T} \cdot A_K$

FORDERUNGEN AN EINEN TEMPERATURKOMPENSATIONSWERKSTOFF:

1. GEEIGNETE CURIETEMPERATUR
2. GROSSES $\partial B_K/\partial T$

THERMOPERM: $\partial B_K/\partial T$ = 7 mT/K   MN-ZN-FERRIT: $\partial B_K/\partial T$ = 3 mT/K

	KOERZIT	KOEROX	KOERFLEX	KOERMAX	Sm_2Co_{17}	CrFeCo	MnAlC
Curietemperatur T_c °C	700-900	450	700	710	800-900	620-680	300-330
TK(J_s) %/K 0-100 °C	-0,02	-0,20	-0,01	-0,04	-0,03	-0,03 bis -0,05	-0,10
TK($_JH_c$)%/K 0-100°C	+0,03 bis -0,07	+0,20 bis +0,50	~0	-0,3	-0,20 bis -0,30	-0,09	-0,15 bis -0,20
Max. Einsatz-temperatur T °C	~500	~300	500	~250	(~200)	~500	(100 bis 150)
Gefügeinstabilität bei T °C	550	1100	520	250	(250)	510	530

KRUPP WIDIA

Temperaturdaten verschiedener Dauermagnetwerkstoffe

MAGNET-WERKSTOFFE

Für Dauermagnete relevante Normen

Gebiet	Bundesrepublik	International
Werkstoffe	DIN 17 410 (5/77)	IEC 68(CO)7 (8/75)
Bauformen	DIN 42 026/1 (9/77)	–
Magn. Messungen	DIN 50 470 (E 12/75) DIN 50 471 (3/71)	IEC 68(CO)12 (1/77)
Begriffe, Einheiten	DIN 1325 (1/72) DIN 1339 (11/71)	ISO 1000 (73) IEC Publ. 50(901) (73) " " 50(901A)(75)

The permanent magnet circuit

1. Materials

2. Design

2.1. Methods

2.1.1. Conventional

2.1.2. Analytical

2.1.3. Numerical

2.2. Example (Core magnet assembly)

2.2.1. Conventional

2.2.2. Analytical

2.2.3. Numerical

3. Applications

1. Conventional method employed for the design of magnet assemblies

Combining the equations of
magnetic flux/magnetomotive force
for the magnet assembly.

$$\oint \mathfrak{B}\, d\mathfrak{A} = 0 \qquad \oint \mathfrak{H}\, d\mathfrak{s} = 0$$

Results: Load line; operating point;
air gap flux density.

Problems: Evaluation of leakage factor;
accuracy of results.

Advantages: No computer program and no
mathematical experience needed.

Magnetostatic circuit

$\oint \vec{B}\, d\vec{A} = 0 \longrightarrow B_m A_m = B_g A_g + B_\ell A_\ell = \sigma B_g A_g$

$\sigma > 1$: Leakage factor ($\sigma \sim ?$)

$\oint \vec{H}\, d\vec{s} = 0 \longrightarrow -H_m \ell_m = H_g \ell_g + H_{Fe} \ell_{Fe} = \gamma H_g \ell_g$

$\gamma > 1$: Mmf - factor ($\gamma \sim 1{,}15$)

Air gap energy: $\frac{1}{2} \mu_0 H_g^2 = \frac{1}{2} \cdot \frac{(B_m H_m) V_m}{\sigma \gamma \cdot V_g}$

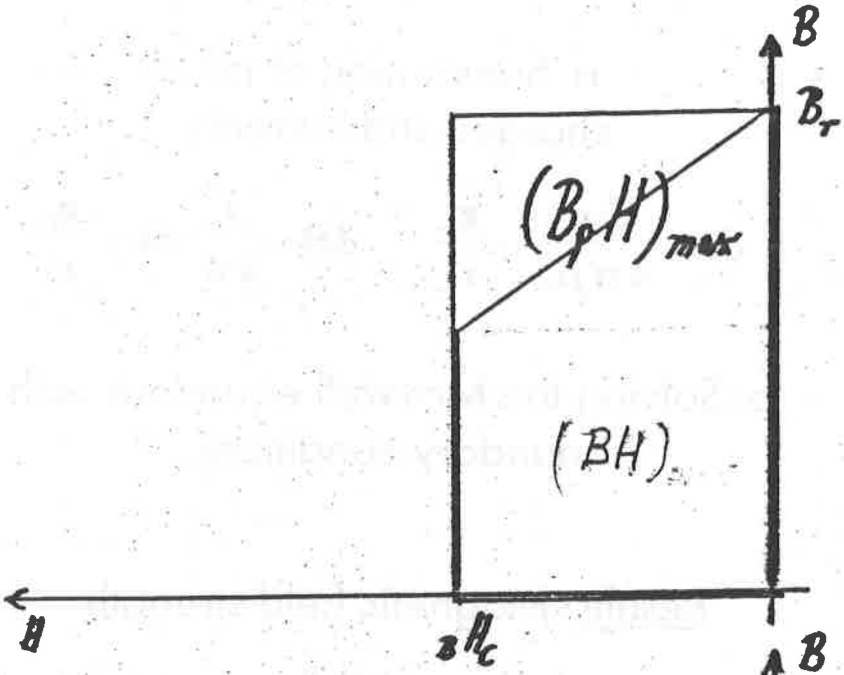
Load line: $\frac{B_m}{-\mu_0 H_m} = \frac{\sigma A_g \ell_m}{\gamma A_m \ell_g}$

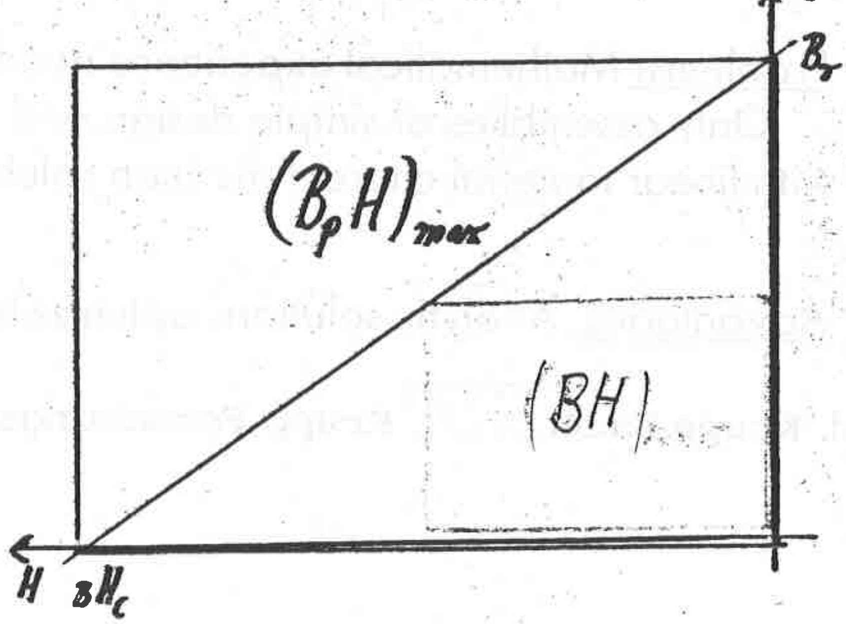
Demagnetization curve: $B = B(H)$

Working point $(B_m; H_m)$: Intersection of load line and demagnetization curve

$\oint \vec{H} d\vec{l} = ni$

$(BH)_{max}$ and $(B_pH)_{max}$





2. Analytical methods employed for the design of magnet assemblies.

a. Summation of all charges and currents:

$$d\mathbf{H} = \frac{dm}{4\pi\mu_0} \cdot \frac{\mathbf{r}_0}{r^2} \qquad d\mathbf{H} = \frac{I}{4\pi} ds \times \frac{\mathbf{r}_0}{r^2}$$

b. Solving the Maxwell equations with boundary conditions.

Results: Magnetic field strength

Problems: Mathematical experience needed ; Only assemblies of simple design and with linear material characterization soluble.

Advantages: Analytic solutions optimizable.

3. Numerical methods employed for the design of magnet assemblies.

a. Summation method.

Summation of all charges and currents.

Problems: Iteration for linear material characterization.

Advantages: Only subdivision of magnetic materials/coils

b. Finite difference method.

Change from differential to difference equations.
Problems: Boundary conditions; interfaces.

c. Finite element method.

Minimizing the energy/calculus of variation.

Results: Magnetic field strength (a);
Scalar or vector potential (b),(c).

Problems: Computer/computer program needed;
Optimizing by repeated calculations.

Advantages: Each problem soluble.

Finite element method

Total energy = f(potential) = Minimum.

$$\text{Total energy} = \sum_{\text{Finite elements}} \text{Energy}.$$

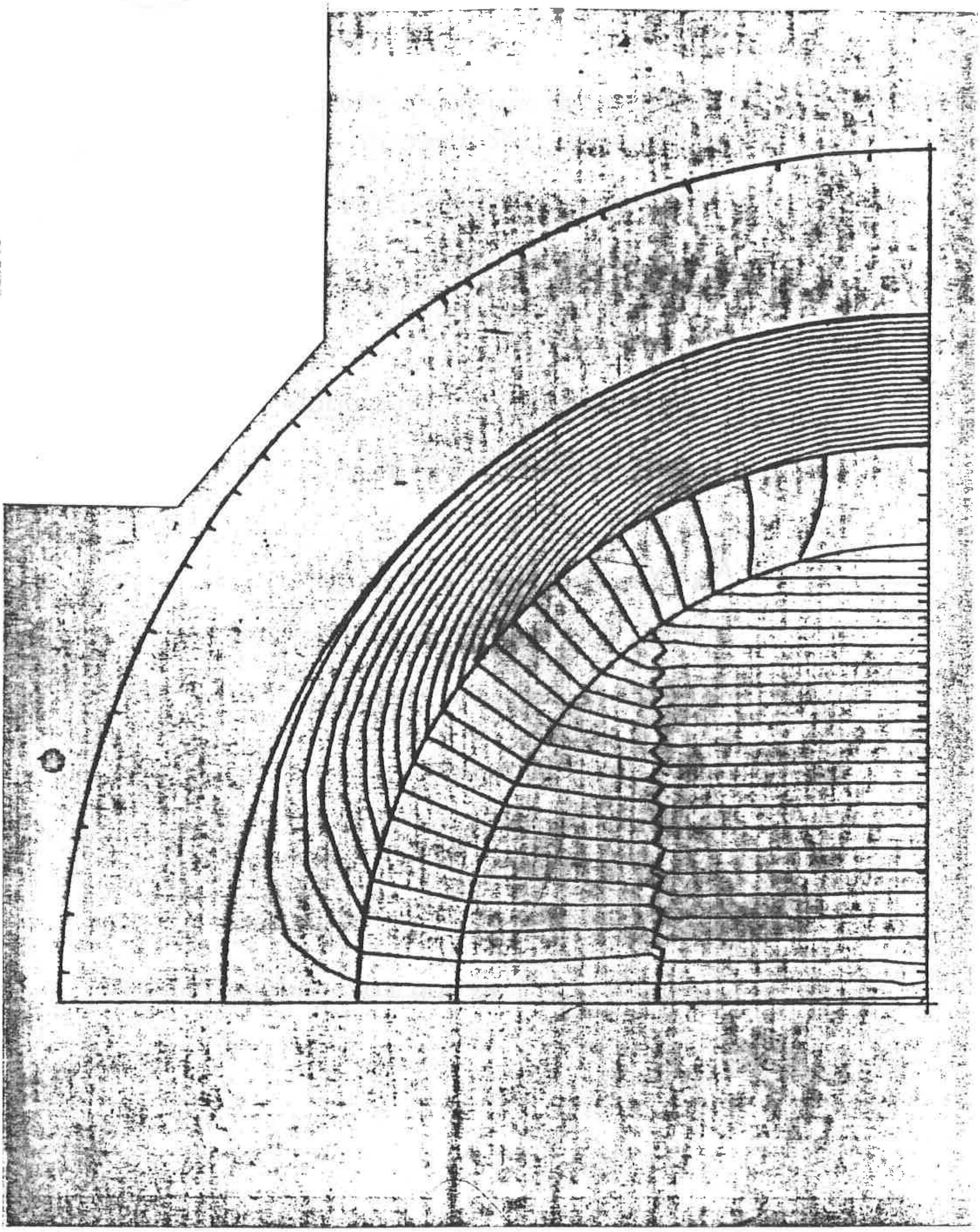
Energy = f(potentials in the nodes).

$$\frac{\partial \text{ total energy}}{\partial \text{ node potentials}} = 0 \Rightarrow \text{System of equations.}$$

Number of nodes = Number of unknowns.

1.step: Generating the grid;
2.step: Setting up and solving the system of equations;
3.step: Computing the magnetic field strength H;
4.step: Only for nonlinear material characterization:
Input of new material data according to H.

5.step: Compare 2.step
6.step: Compare 3.step
7.step: Compare 4.step
} Iteration



Dependence of magnetization on magnetic field strength

a) Isotropic magnetic material:

Susceptibility χ

$M = \chi \cdot H$: Measurement

b) Anisotropic magnetic material:

Susceptibility tensor $\boldsymbol{\chi}$

$$\mathbf{M} = \boldsymbol{\chi} \cdot \mathbf{H}$$

$$M_x = \chi_{xx} \cdot H_x + \chi_{xy} \cdot H_y + \chi_{xz} \cdot H_z$$

$$M_y = \chi_{yx} \cdot H_x + \chi_{yy} \cdot H_y + \chi_{yz} \cdot H_z$$

$$M_z = \chi_{zx} \cdot H_x + \chi_{zy} \cdot H_y + \chi_{zz} \cdot H_z$$

Approximation:

$M_x \approx \chi_{xx} \cdot H_x$: Measurement

$M_y \approx 0$

$M_z \approx 0$

Abstract:

Using the example of a core magnet system, consisting of a diametrically magnetized cylindrical magnet and a concentric magnetically soft magnetic return path, the three commonly used methods for computing permanent magnet systems are outlined.

The advantages and disadvantages of the conventional methods, analytic and numerical computation, are described with mention of their scope and limitations.

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Conventional design method

<u>Magnetomotive force:</u> $\tau \cdot H_m L_m = -H_g L_g$; $\tau \approx 0{,}85$

<u>Flux relation:</u> $\sigma \cdot B_m A_m = \mu_o H_g A_g$; $\sigma \leq 1{,}00$

<u>Load line:</u>
$$\frac{B_m}{\mu_o H_m} = \frac{\tau}{\sigma} \; \frac{A_g}{A_m} \; \frac{L_m}{L_g}$$

<u>Gap energy:</u> $\mu_o H_g^2 V_g = \tau \cdot \sigma \left| B_m H_m \right| \cdot V_m$

$$L_m = \frac{\pi}{4D}(D^2 - d^2) \quad ; \quad A_m = (D-d) \cdot h$$

$$L_g = D_{Fe} - D \quad ; \quad A_g = \frac{\pi h}{4}(D_{Fe} + D)$$

$D_{Fe} = 20\,mm$; $D = 16\,mm$; $d = 3{,}8\ (0{,}0)\ mm$

$h = \infty \Rightarrow \sigma = 1{,}00$; $\tau = 0{,}85$

$B_r = 920\,mT$; $\mu_p = 1{,}00$

$B_m/(-\mu_o H_m) = 5{,}84\ (4{,}72)$

$H_m = -108\ (128)\ kA/m$; $B_m = 793\ (759)\ mT$

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$A_m = (D-d)\,h$ ist [illegible] [illegible]

$A_m = D \cdot h$ ist [illegible] [illegible].

<u>[illegible]</u> $\frac{L_m}{A_m} = \frac{\pi}{4D} \frac{(D-d)(D+d)}{(D-d) \cdot h} = \frac{\pi (D+d)}{4Dh}$ [illegible]

$$H_g = \frac{\hat{H}_g}{\pi/2} \cdot \int_0^{\pi/2} \sin\varphi \cdot d\varphi \quad ; \quad \hat{H}_g = \frac{\pi}{2} \cdot H_g$$

$H_g = 272\,(342)$ kA/m ; $\hat{H}_g = 427\,(537)$ kA/m

Analytically computed: $H_r(9\text{mm};90^\circ) = 494(524)$ kA/m

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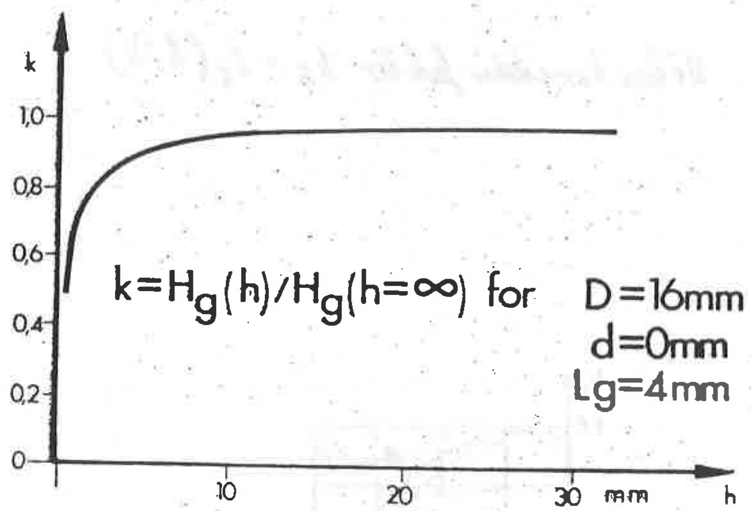
Reduction of H_g ($h=\infty$) for finite h:



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Die Flüsse Φ_N, Φ_{STR} sind proportional den Leitwerten des Nutz- und des Streuluftspaltes $R = \frac{L}{\mu_0(\mu_r) A}$, $\frac{1}{R} = \frac{\mu_0(\mu_r) A}{L}$

$D = 16\ mm$

$\ell = 2\ mm$

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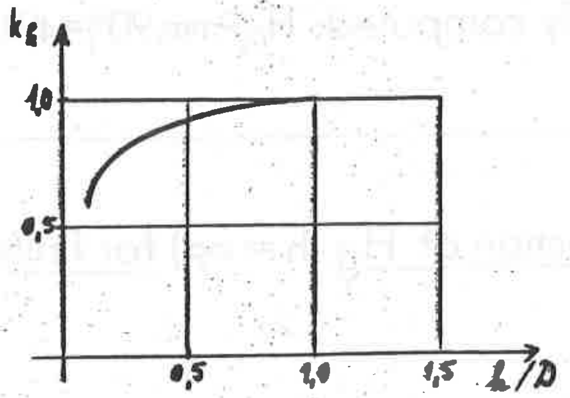
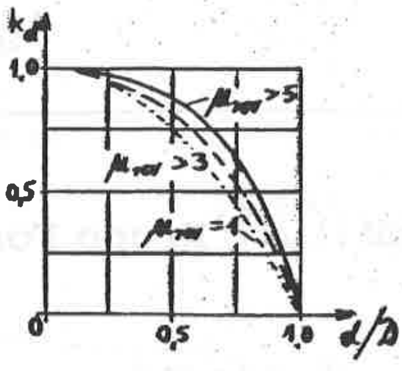
$$H_\ell'(h;d) = H_\ell(h=\infty; d=0) \cdot k_h \cdot k_d$$

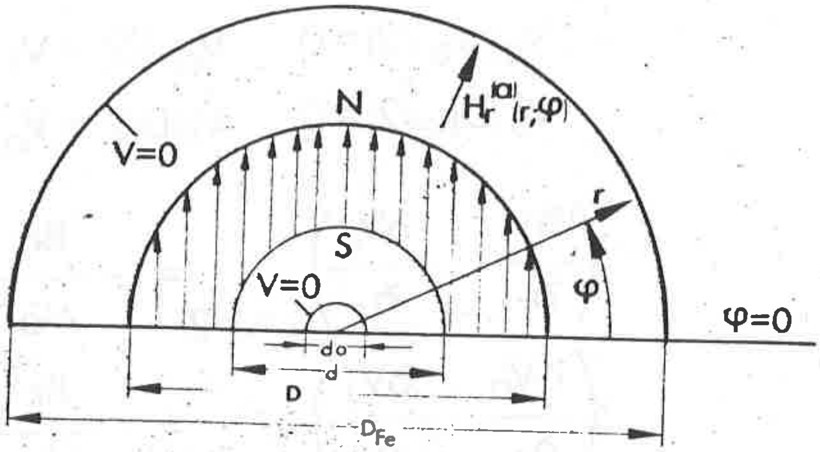


Höhenkorrektürfaktor $k_h = k_h(h/D)$



Lochkorrektürfaktor $k_d = k_d(d/D)$

Analytical solution



Assumptions:

Permanent magnetic material with $\mu_p \approx 1$ (fixed magnetization).

Soft magnetic material with $\mu_r \gg 1$ ($\mu_r = \infty$)

Laplace equation:

$$\Delta V = \frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \cdot \frac{\partial V}{\partial r} + \frac{1}{r^2} \cdot \frac{\partial^2 V}{\partial \varphi^2} = 0$$

Ansatz:

$$V_o = (V_o^+ \cdot r + V_o^- \cdot r^{-1}) \cdot \sin\varphi \qquad d_o \leq 2r \leq d$$

$$V_i = (V_i^+ \cdot r + V_i^- \cdot r^{-1}) \cdot \sin\varphi \qquad d \leq 2r \leq D$$

$$V_a = (V_a^+ \cdot r + V_a^- \cdot r^{-1}) \cdot \sin\varphi \qquad D \leq 2r \leq D_{Fe}$$

Boundary conditions:

$$V_o(d_o/2)=0 \qquad V_o(d/2)=V_i(d/2)$$
$$V_a(D_{Fe}/2)=0 \qquad V_i(D/2)=V_a(D/2)$$

$$\left(\frac{\partial V_i}{\partial r}-\frac{\partial V_o}{\partial r}\right)_{r=d/2} = -\frac{Br}{\mu_o}\cdot\sin\varphi$$

$$\left(\frac{\partial V_a}{\partial r}-\frac{\partial V_i}{\partial r}\right)_{r=D/2} = \frac{Br}{\mu_o}\cdot\sin\varphi$$

Solutions:

Bore without iron:

$$H_r^{(a)}(r;\varphi)=\frac{B_r}{2\mu_o}\cdot\frac{D^2-d^2}{D_{Fe}^2}\cdot\left\{1+\left(\frac{D_{Fe}}{2r}\right)^2\right\}\cdot\sin\varphi$$

Bore filled with iron $(d=d_o)$:

$$H_r^{(a)}(r;\varphi)=\frac{B_r}{2\mu_o}\cdot\frac{D^2-d^2}{D_{Fe}^2-d^2}\cdot\left\{1+\left(\frac{D_{Fe}}{2r}\right)^2\right\}\cdot\sin\varphi$$

Effect of iron in the bore:

$$\frac{H_r^{(a)}(\text{with iron})-H_r^{(a)}(\text{without iron})}{H_r^{(a)}(\text{without iron})}=\frac{1}{(D_{Fe}/d)^2-1}$$

Feldstärke im Luftspalt

$$H_r(r;\varphi) = \frac{B_r}{2\mu_0} \cdot \frac{D^2 - d^2}{u_a^+ D_{Fe}^2 - u_i^- d^2} \cdot \left\{ 1 + u_a^+ \left(\frac{D_{Fe}}{2r} \right)^2 \right\} \cdot \sin\varphi$$

$$H_\varphi(r;\varphi) = \frac{B_r}{2\mu_0} \cdot \frac{D^2 - d^2}{u_a^+ D_{Fe}^2 - u_i^- d^2} \cdot \left\{ 1 - u_a^+ \left(\frac{D_{Fe}}{2r} \right)^2 \right\} \cdot \cos\varphi$$

$$u_a^+ = \frac{\mu_r^{(a)} + 1}{\mu_r^{(a)} - 1} \qquad u_i^- = \frac{\mu_r^{(i)} - 1}{\mu_r^{(i)} + 1}$$

$$= 1 \qquad\qquad = 1 \qquad \text{für } \mu_r = \infty$$

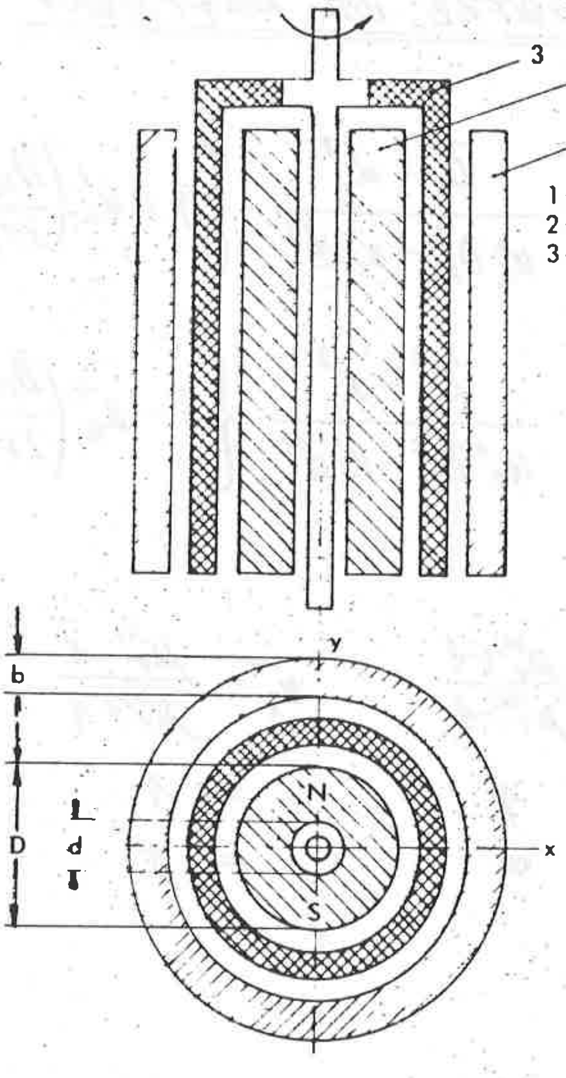
$$= \infty \qquad\qquad = 0 \qquad \text{für } \mu_r = 1$$

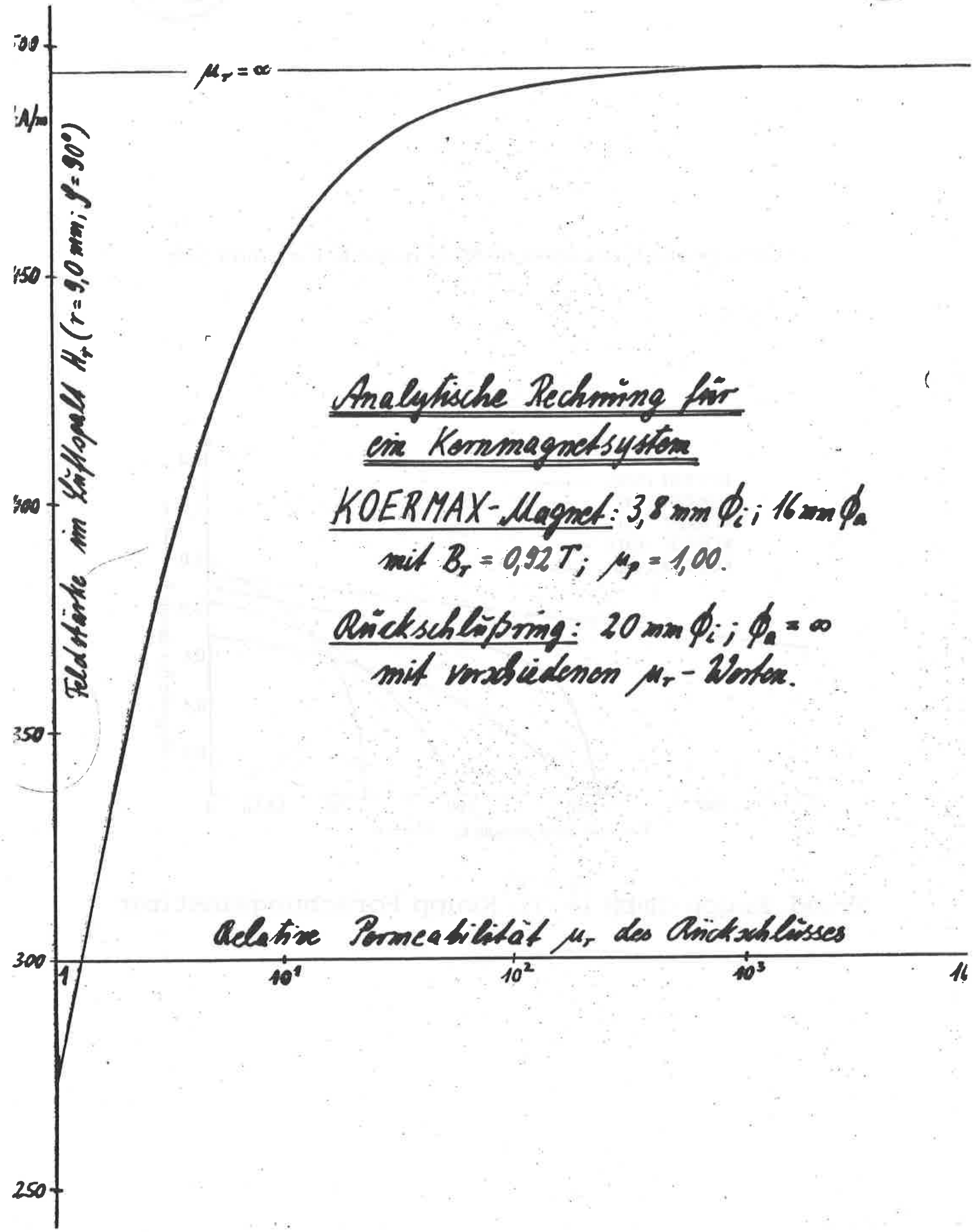
Innen Luft $\mu_r^{(i)} = 1$

RESERVE

Moving-coil motor

schematic cross-section

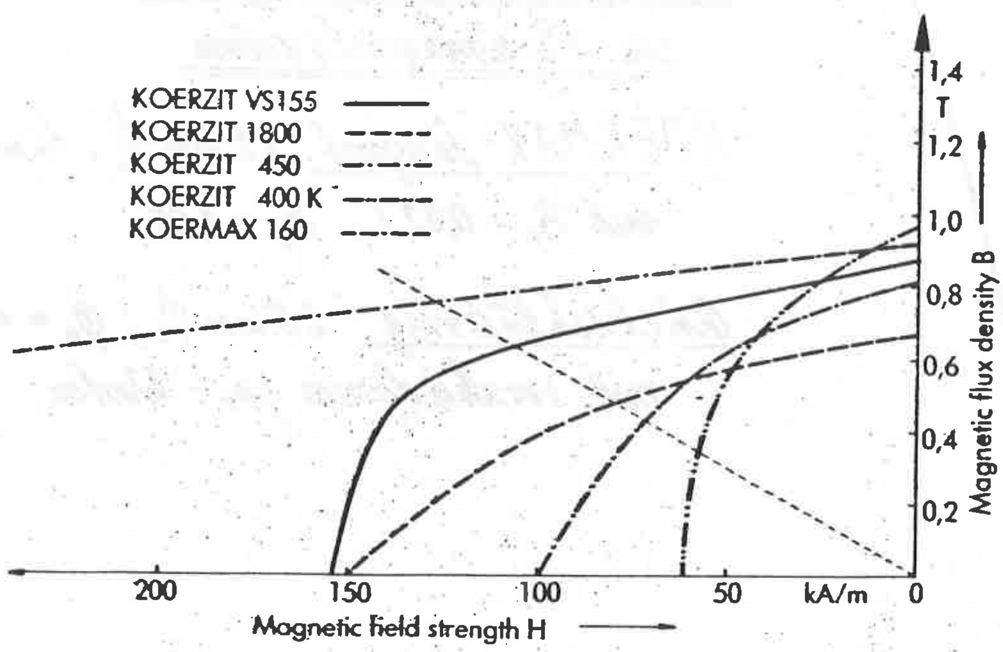




00
A/m
450
400
350
300
250
Feldstärke im Luftspalt H_r (r = 9,0 mm; φ = 90°)
$\mu_r = \infty$
Analytische Rechnung für ein Kernmagnetsystem
KOERMAX-Magnet: 3,8 mm Φ_i; 16 mm Φ_a
mit B_r = 0,92 T; μ_r = 1,00.
Rückschlußring: 20 mm Φ_i; $\Phi_a = \infty$
mit verschiedenen μ_r-Werten.
Relative Permeabilität μ_r des Rückschlusses
1
10^1
10^2
10^3
1

32

Demagnetization curves of AlNiCo and RECo5-materials



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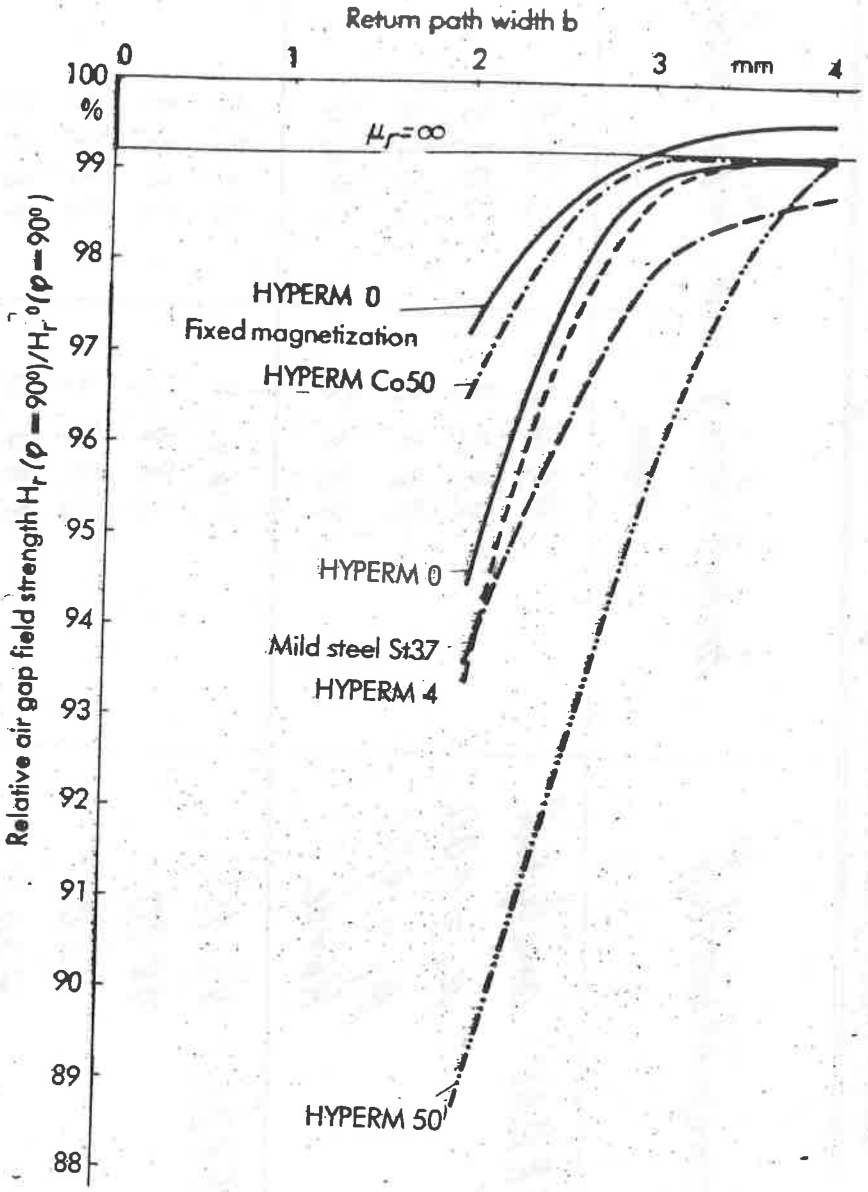
Luftspaltfeldstärke H_r ($r = 9\,mm$; $\varphi = 90°$) in kA/m

Dauermagnetwerkstoff	Innenbohrung mit Eisen gefüllt: nein	ja
KOERMAX analytisch	494,0	512,5
$\mu_p = 1{,}00$	490,3	507,5
$\mu_p = 1{,}05$	484,8	502,4
Kurve	488,2	506,0
KOERZIT VS 155	366,9	398,4
1800	284,5	303,9
450	245,1	255,7
400 K	194,0	187,2

KOERMAX 160 core magnet system with various materials of the return path ring



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H_r^c: Feldstärke im Luftspalt eines KOERMAX-Systems mit innerer Magnetisierung des KOERMAX und $\mu_r = \infty$ für das Rückschluß-material.

35

KOERMAX 160 core magnet system with various materials of the return path ring

Air gap field strength $H_r(r = 9\ mm; \varphi = 90°)$ in kA/m

Soft magnetic material	Return path width b in mm		
	2	3	4
HYPERM Co50	476,7	489,8	490,0
HYPERM 0	466,3	488,7	489,8
HYPERM 4	461,3	487,5	490,0
HYPERM 50	437,9	472,4	489,9
Mild steel St 37	462,4	483,7	487,9

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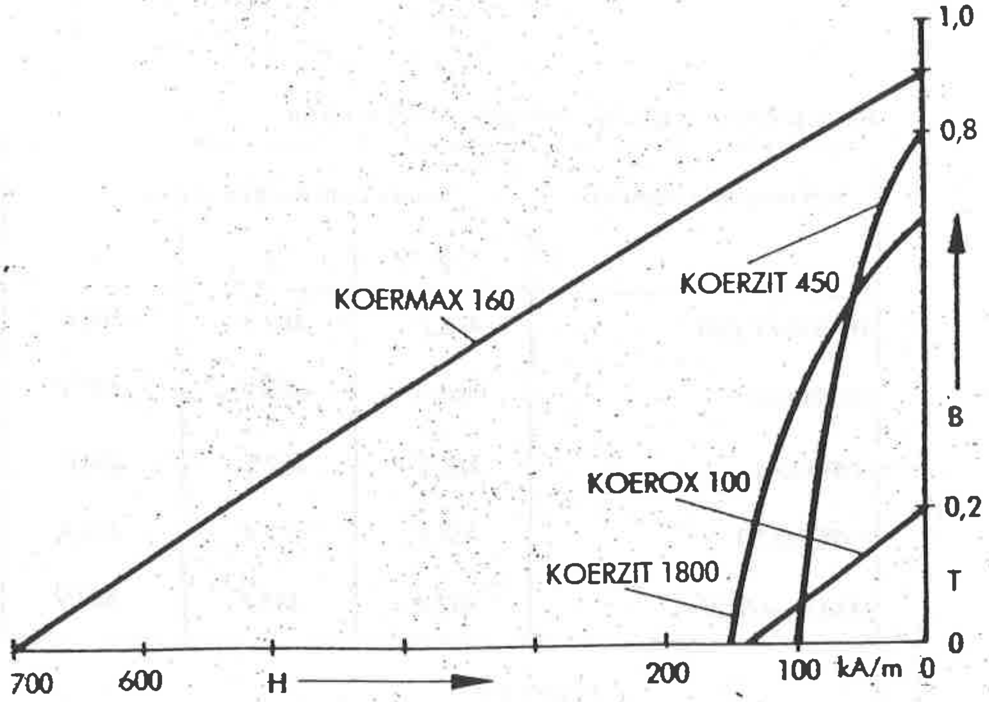
Demagnetization curves
for some permanent magnet materials



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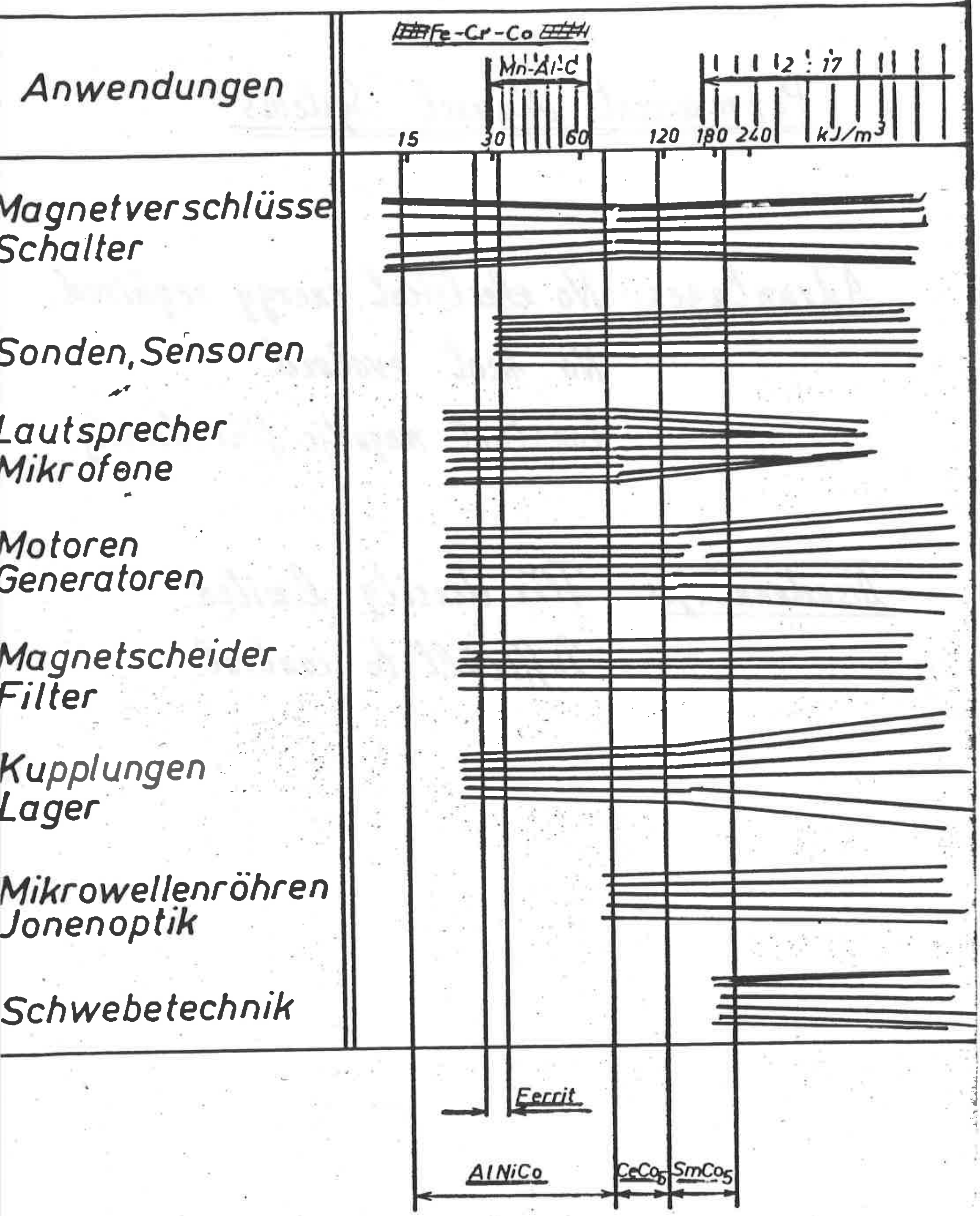
Permanent Magnet Systems

Advantages: No electrical energy required.
No heat evolved.
Constant magnetic flux density.

Disadvantages: Flux density limited.
Difficult to control.


Anwendungen
Fe-Cr-Co
Mn-Al-C
2 : 17
15
30
60
120
180
240
kJ/m³
Magnetverschlüsse
Schalter
Sonden, Sensoren
Lautsprecher
Mikrofone
Motoren
Generatoren
Magnetscheider
Filter
Kupplungen
Lager
Mikrowellenröhren
Jonenoptik
Schwebetechnik
Ferrit
AlNiCo
CeCo5
SmCo5

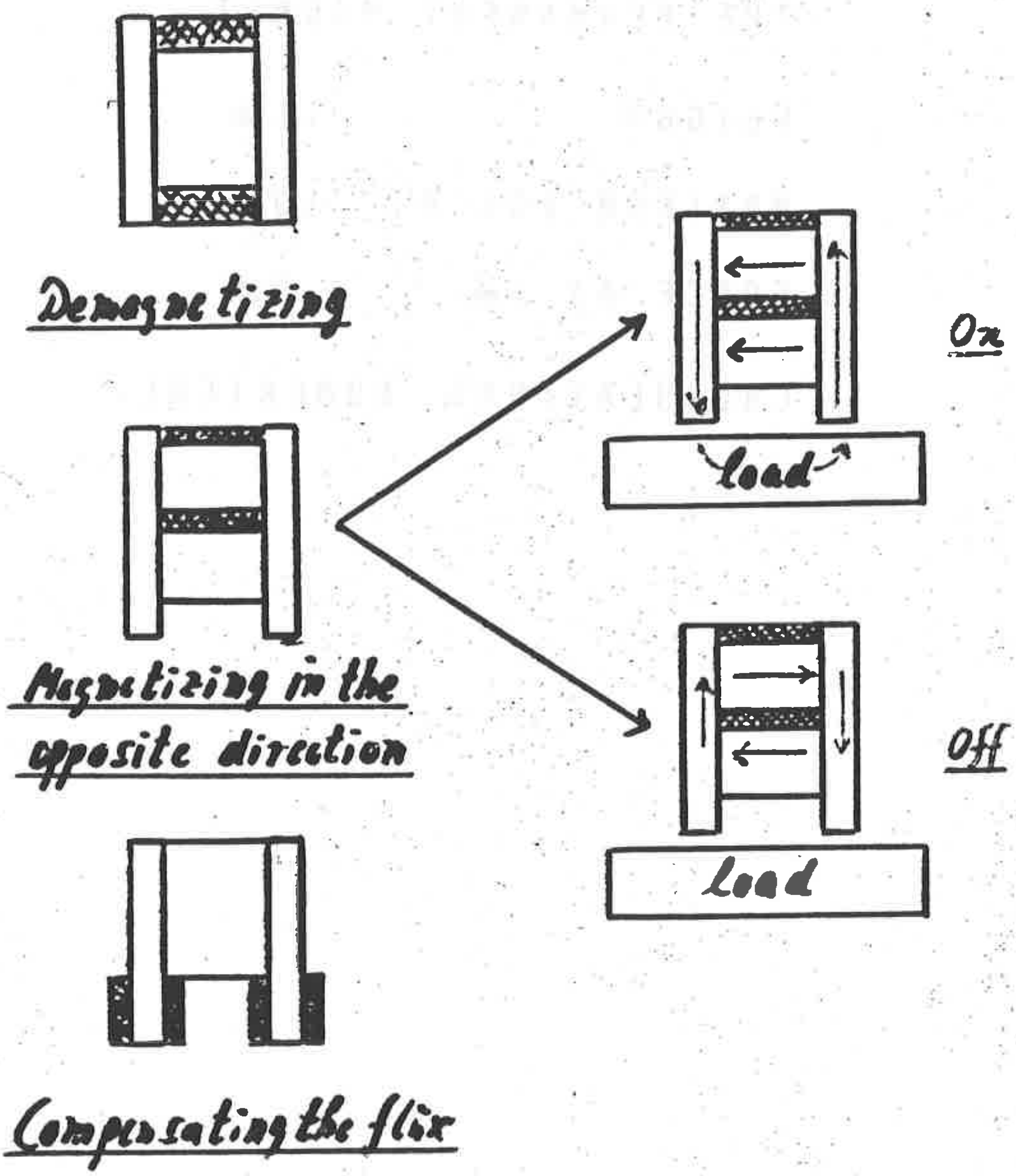
SWITCHABLE LIFTING MAGNET

CONTROLLED BY TURNING THE PERMANENT MAGNET

WEIGHT:	11 KG
MAXIMUM FORCE:	10 KN
FORCE AT 1 MM:	2 KN

CALCULATIONS: NUMERICAL

Switchable permanent magnet systems.



(41)

COAXIAL SYNCHRONOUS COUPLING

NUMBER OF POLES: 120

AIR GAP: 2 MM

MAXIMUM TORQUE: 4 kN·M

CALCULATIONS: ANALYTICAL

NUMERICAL

COAXIAL SYNCHRONOUS COUPLING

TORQUE IN kN·m, NORMALIZED TO
A COUPLING LENGTH A = 96 mm

MEAN POLE DISTANCE B = 13.5 mm

	A IN MM	A/B	NUMBER OF BACK-CIRCUITS 2	1	0
ANALYTICAL	10	0.75	2.88	2.25	1.81
"	96	7.1	4.53	3.44	2.60
"	∞	∞	4.64	3.49	2.62
NUMERICAL	∞	∞	4.615	3.412 3.488	2.582
MEASURED	96	7.1	4.65	-	-

ELBA Nr. 71490

RADIAL MAGNETIC BEARING

AXIALLY MAGNETIZED CONCENTRIC RINGS WITHOUT IRON

AIR GAP: 2 MM

RADIAL STIFFNESS: 22 KN/M

CALCULATIONS: ANALYTICAL WITH NUMERICAL INTEGRATION

LIMITING VALUES OF MAGNETIC FORCES

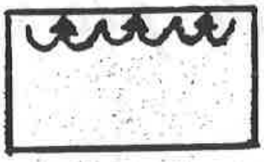
Attraction or Repulsion with Permanent Magnets Attraction with Soft Magnetic Materials	$M \cdot A \cdot \kappa$ $\kappa \rightarrow 1$
Shear Force	$M \cdot A \cdot \kappa$ $\kappa \rightarrow 0.75$
Torque	$M \cdot A \cdot \kappa \cdot R$ $\kappa \rightarrow 0.75$
Radial Bearing	$M \cdot A \cdot \kappa$ $\kappa \rightarrow 0.32$

Material Factor	$M = B_R^2 / 2\mu_0$
Area of Air Gap	A
Mean Radius of Air Gap	R
Geometric Factor	κ

Magnetic fields with permanent magnets

Methods

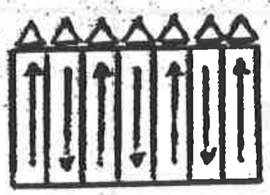
1. without soft magnetic material



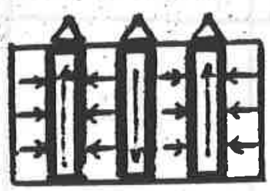
In isotropic mater.

with "blocking" magnets

2. With soft magnetic material



with pole-pieces



with pole-pieces

Magnetic fields with permanent magnets

Maximum field values

	Pole-pieces			
	without		with	
	only PM	with SM	only PM	with SM
plane surface	$B_r/2$	$J_s/2$	∞	∞
air gap	B_r	J_s	∞	∞

Remanenz of permanent magnet material (PM): B_r

Saturation of soft magnetic material (SM): J_s

COMPUTATIONAL METHOD

ASSUMPTION: FIXED MAGNETIZATION

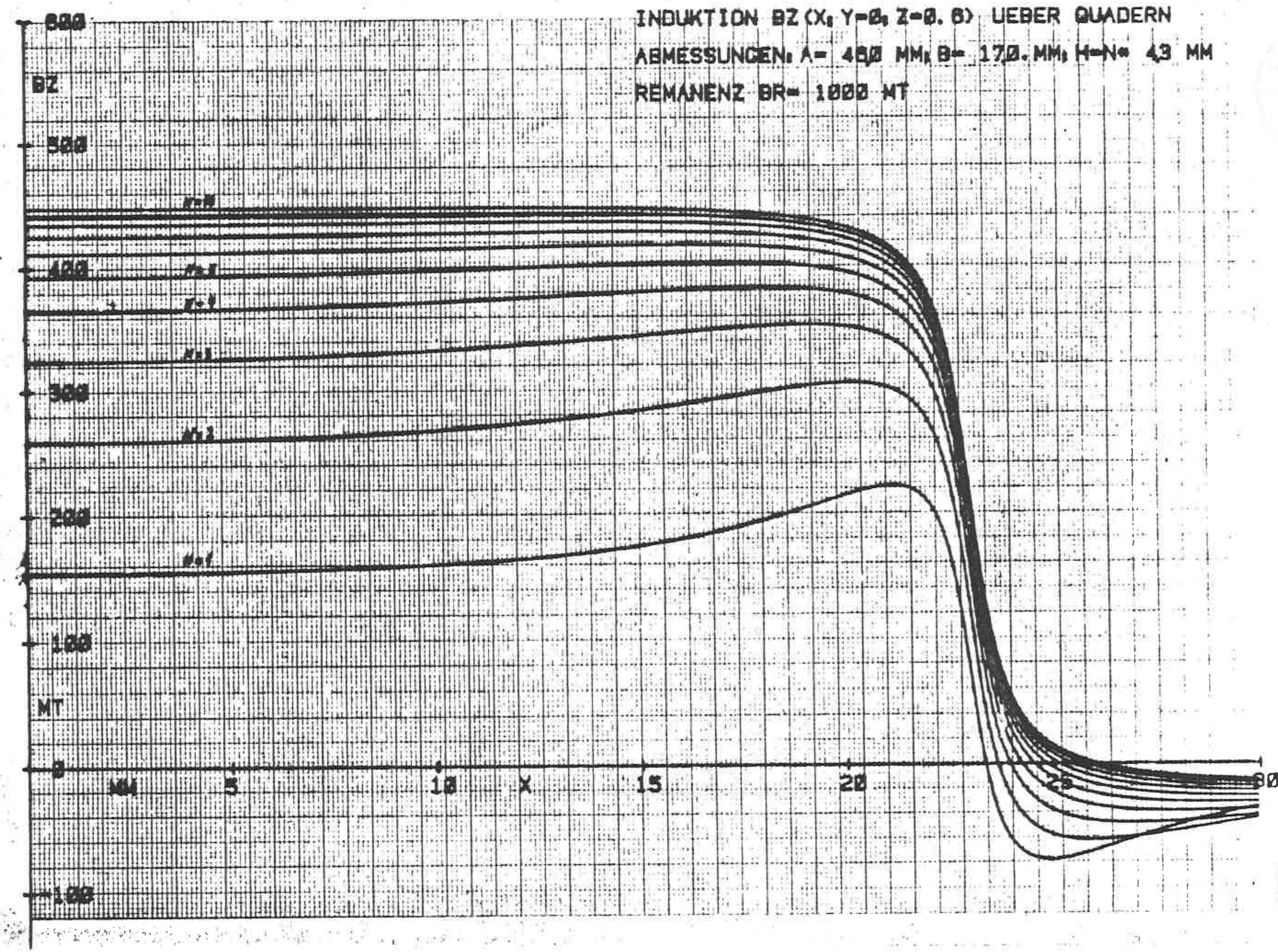
FLUX DENSITY OF A BAR MAGNET:

$$B_Z(X,Y,Z) = \frac{J_R}{4\pi} \text{ARCTAN}\left(\frac{(X-X').(Y-Y')}{(Z-Z').S}\right)\Bigg|_{-A}^{+A}\Bigg|_{-B}^{+B}\Bigg|_{-H}^{+H}$$

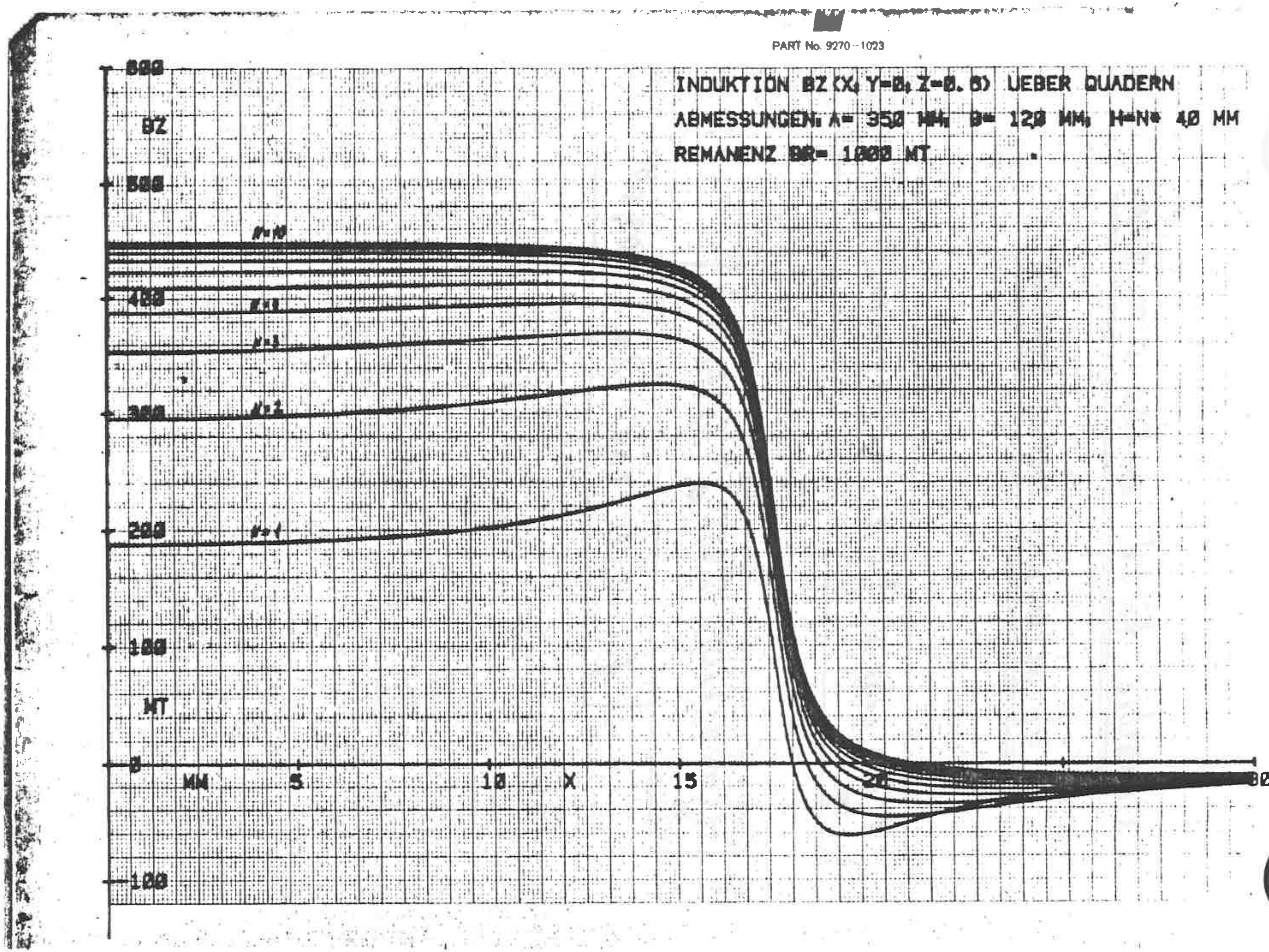
$$B_X(X,Y,Z) = \frac{J_R}{4\pi} \text{LN}\left((Y-Y')+S\right)\Bigg|_{-A}^{+A}\Bigg|_{-B}^{+B}\Bigg|_{-H}^{+H}$$

$$B_Y(X,Y,Z) = \frac{J_R}{4\pi} \text{LN}\left((X-X')+S\right)\Bigg|_{-A}^{+A}\Bigg|_{-B}^{+B}\Bigg|_{-H}^{+H}$$

$$S = \left((X-X')^2 + (Y-Y')^2 + (Z-Z')^2 \right)^{1/2}$$


INDUKTION BZ (X, Y=0, Z=0. 6) UEBER QUADERN
ABMESSUNGEN: A= 480 MM, B= 170. MM, H=N= 43 MM
REMANENZ BR= 1000 MT
BZ
MT
600
500
400
300
200
100
0
-100
MM
5
10
X
15
20
25
30

49


PART No. 9270-1023
INDUKTION BZ (X, Y=0, Z=0.8) UEBER QUADERN
ABMESSUNGEN: A= 350 MM, B= 120 MM, H=N= 40 MM
REMANENZ BR= 1000 MT
BZ
600
500
400
300
200
100
MT
0
-100
MM
5
10
X
15
20
30

49

Magnetic field in the air gap of permanent magnet systems

$$H(r=0;\, z=0) = J\left\{1 - 1/\sqrt{1+(r_0/z_2)^2}\right\}.$$

$$H(r=0;\, z=0) = 0.886\, J \cdot \lg(z_1/z_2)$$

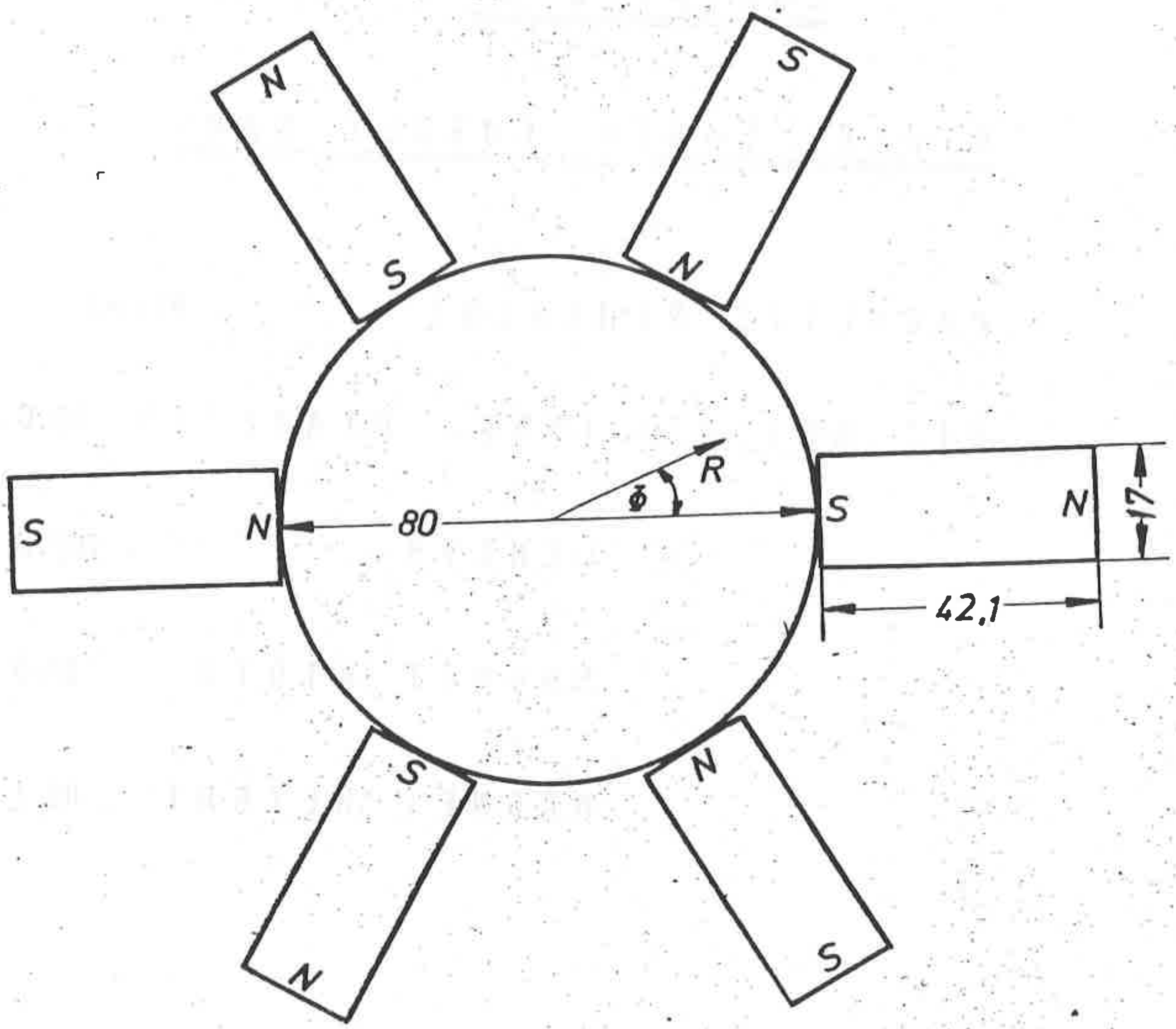
for $z_0 = 0$ and $2\alpha = 109{,}5^\circ$

PERMANENT HEXAPOLE MAGNET

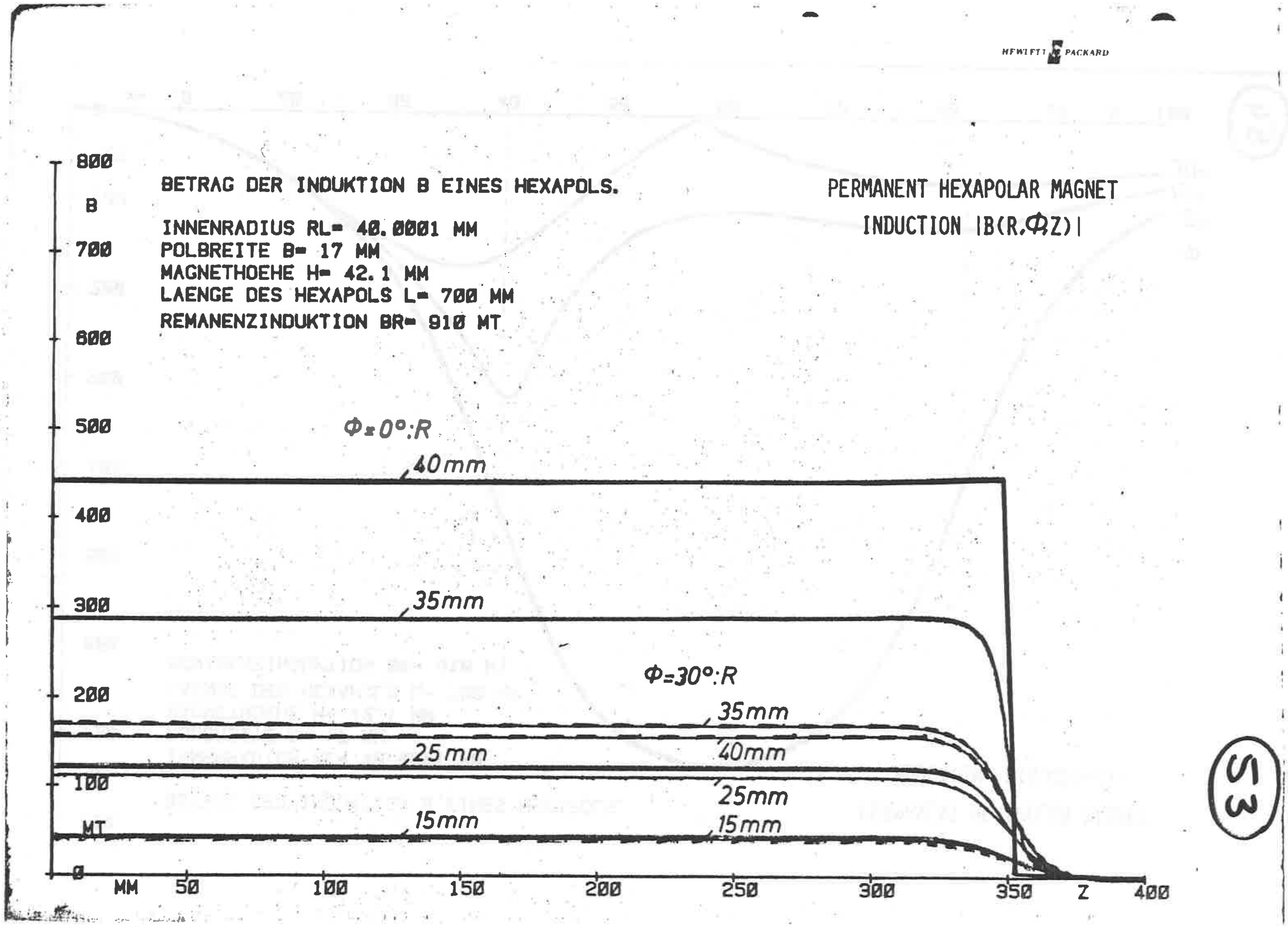
COMPOSED OF

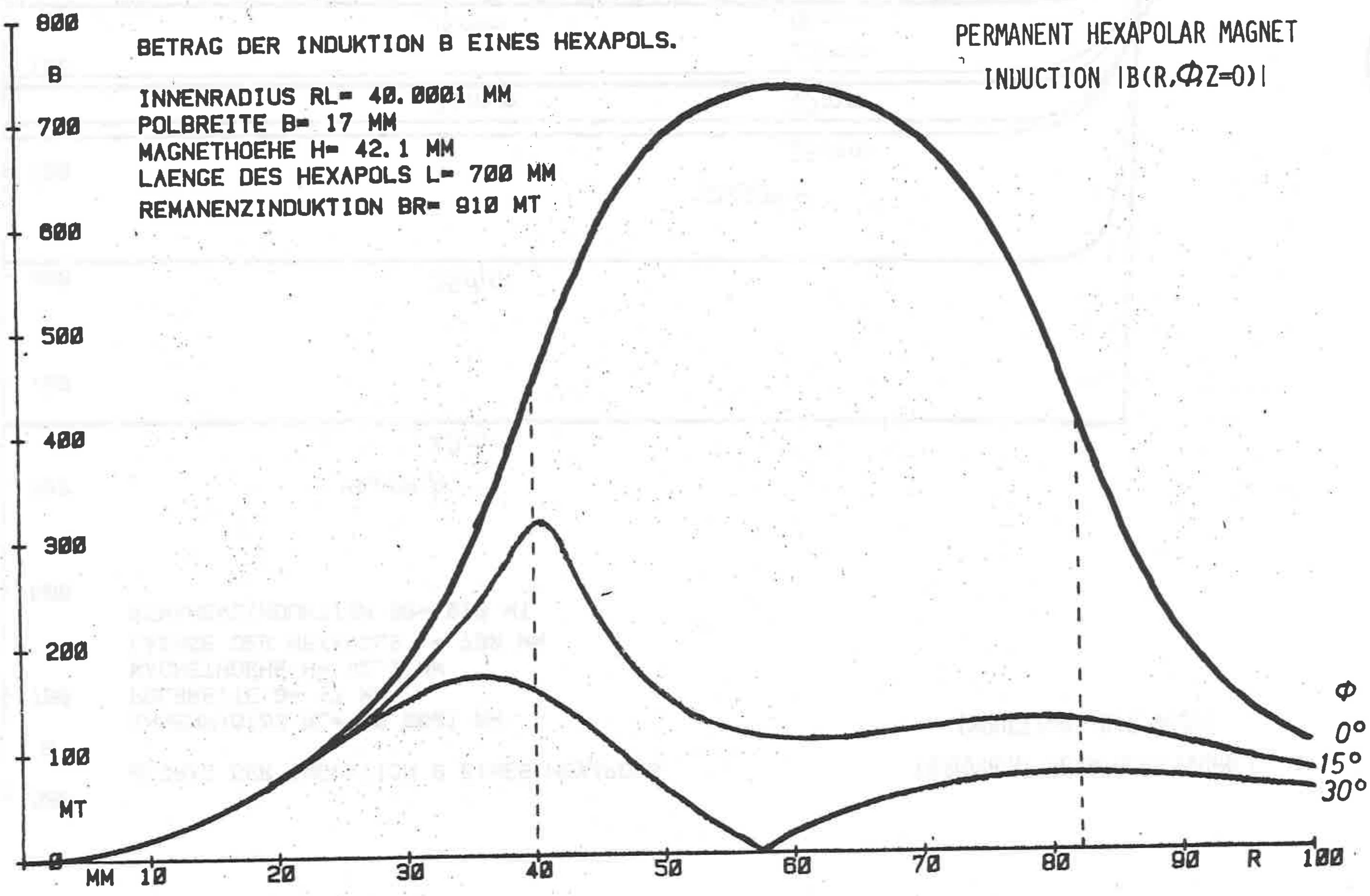
6 RARE EARTH COBALT BARS

MAGNETIC REMANENZ		910 mT
DIMENSIONS:	INNER DIAMETER	80.0 MM
	LENGTH	700.0 MM
	MAGNET WIDTH	17.0 MM
	MAGNET HEIGHT	42.1 MM

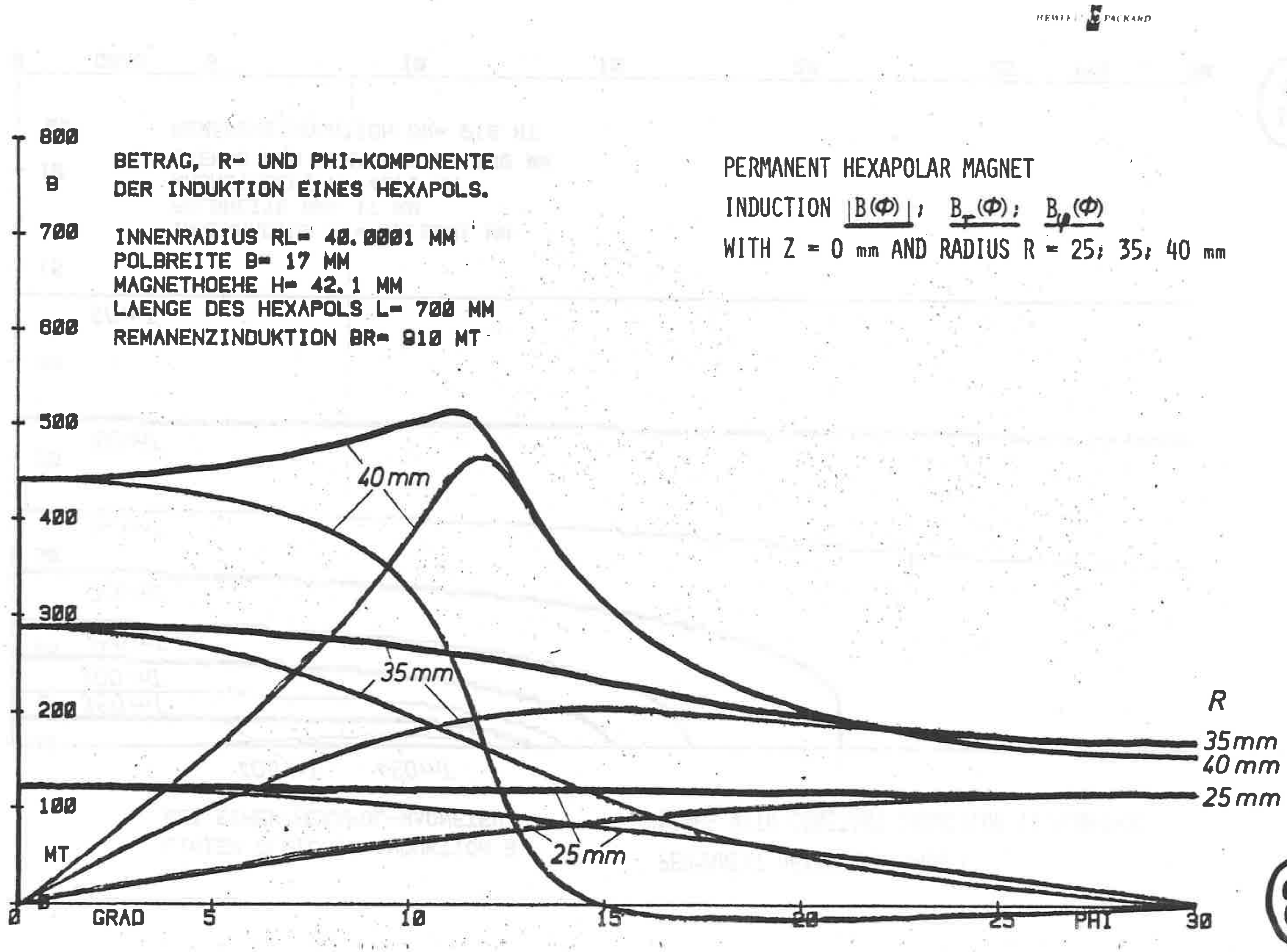


PERMANENT HEXAPOLAR MAGNET
CROSS SECTION


HEWLETT PACKARD
BETRAG DER INDUKTION B EINES HEXAPOLS.
INNENRADIUS RL= 40.0001 MM
POLBREITE B= 17 MM
MAGNETHOEHE H= 42.1 MM
LAENGE DES HEXAPOLS L= 700 MM
REMANENZINDUKTION BR= 910 MT
PERMANENT HEXAPOLAR MAGNET
INDUCTION |B(R,Φ,Z)|
B
800
700
600
500
400
300
200
100
MT
0
Φ=0°:R
40mm
35mm
25mm
15mm
Φ=30°:R
35mm
40mm
25mm
15mm
MM
50
100
150
200
250
300
350
Z
400
53


BETRAG DER INDUKTION B EINES HEXAPOLS.
INNENRADIUS RL= 40.0001 MM
POLBREITE B= 17 MM
MAGNETHOEHE H= 42.1 MM
LAENGE DES HEXAPOLS L= 700 MM
REMANENZINDUKTION BR= 910 MT
PERMANENT HEXAPOLAR MAGNET
INDUCTION |B(R,Φ,Z=0)|
B
MT
800
700
600
500
400
300
200
100
0
MM
10
20
30
40
50
60
70
80
90
R
100
Φ
0°
15°
30°

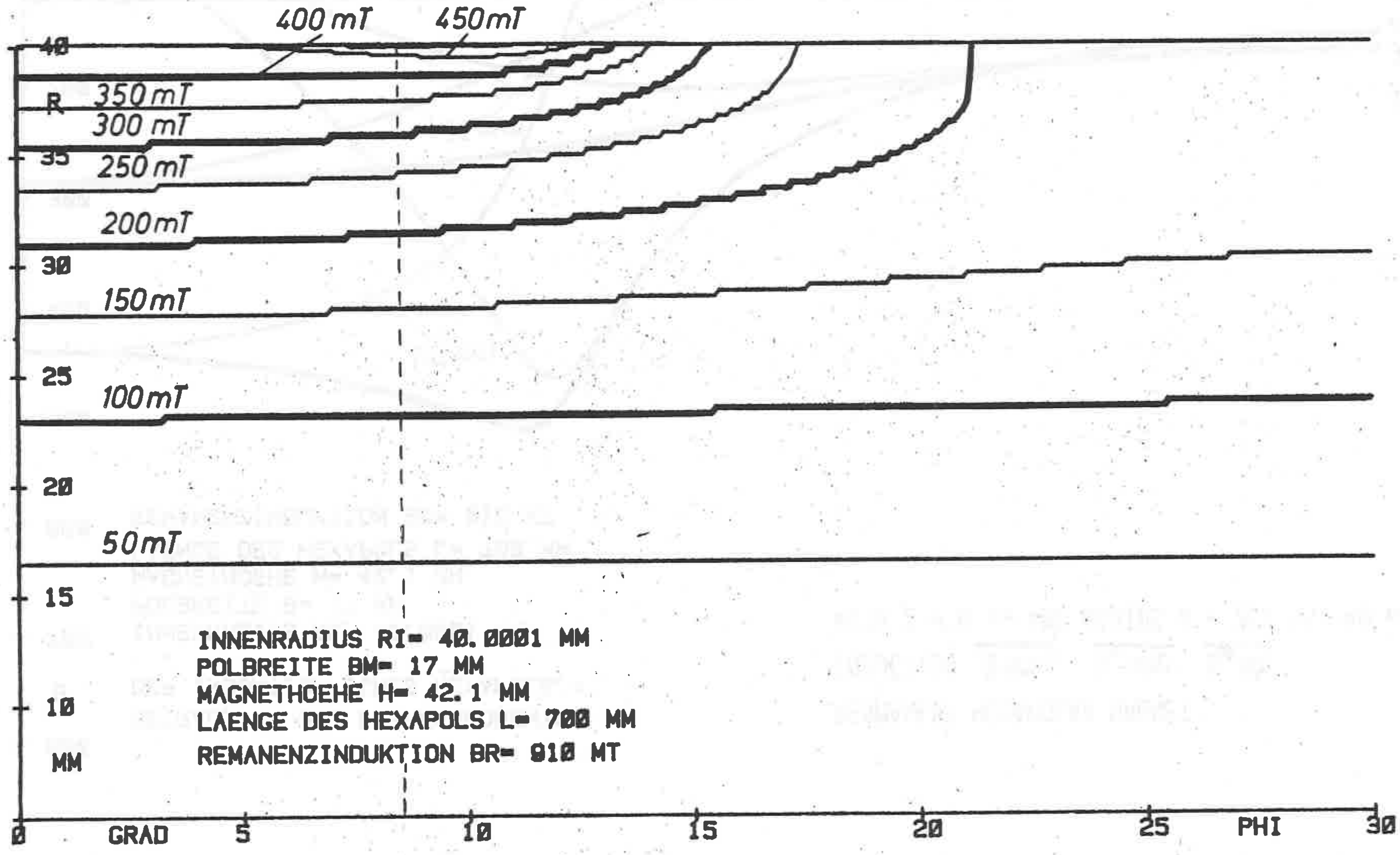
54

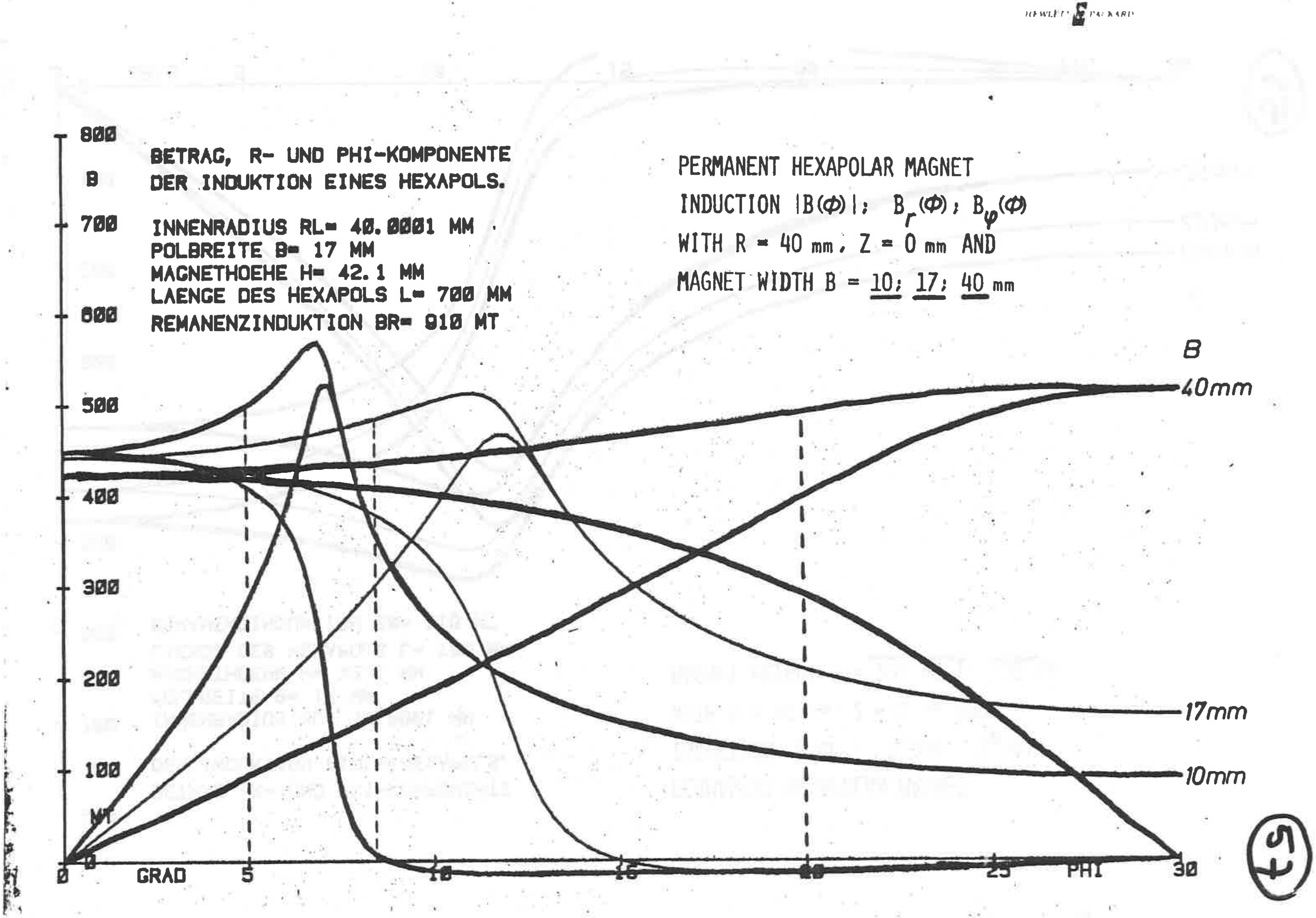


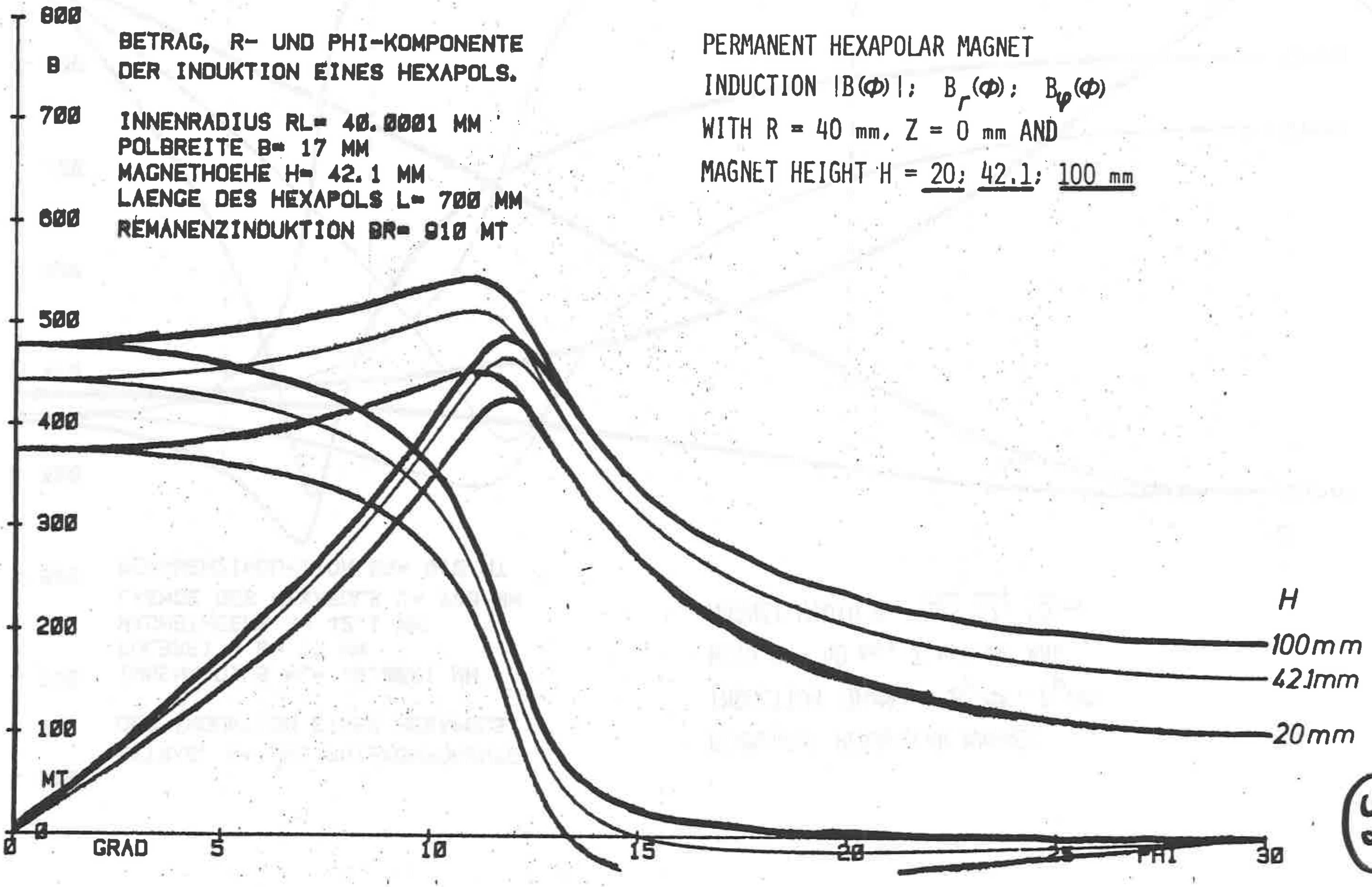
HEWLETT PACKARD
800
B
700
600
500
400
300
200
100
MT
0
GRAD
5
10
15
20
25
PHI
30
BETRAG, R- UND PHI-KOMPONENTE
DER INDUKTION EINES HEXAPOLS.
INNENRADIUS RL= 40.0001 MM
POLBREITE B= 17 MM
MAGNETHOEHE H= 42.1 MM
LAENGE DES HEXAPOLS L= 700 MM
REMANENZINDUKTION BR= 910 MT
PERMANENT HEXAPOLAR MAGNET
INDUCTION |B(Φ)|; B_r(Φ); B_φ(Φ)
WITH Z = 0 mm AND RADIUS R = 25; 35; 40 mm
40mm
35mm
25mm
R
35mm
40mm
25mm

LINIEN GLEICHER INDUKTION B
BEI EINEM HEXAPOL-MAGNETEN.

PERMANENT HEXAPOLAR MAGNET.
LINES WITH CONSTANT INDUCTION |B(R;Φ;Z=0)|

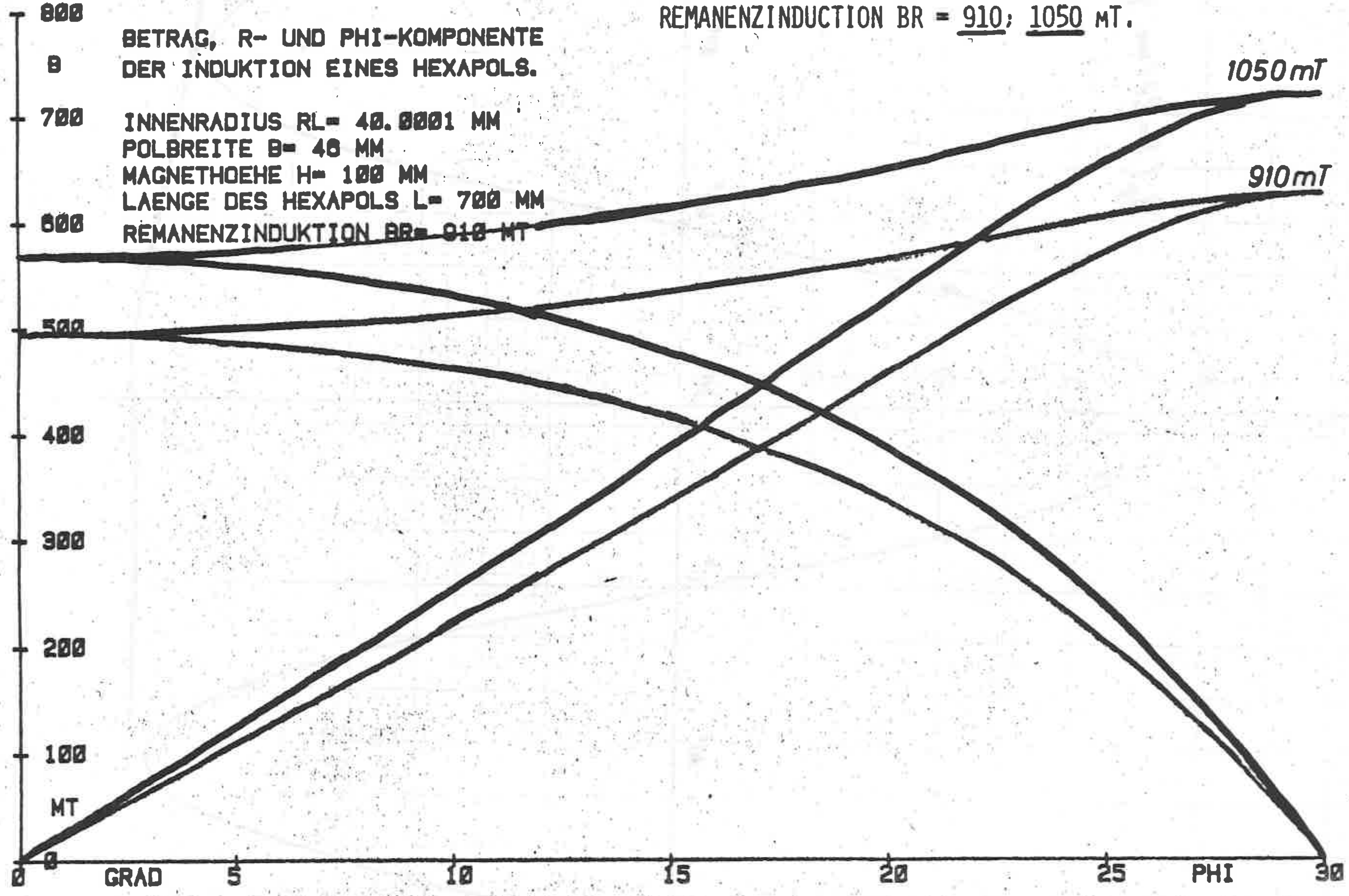


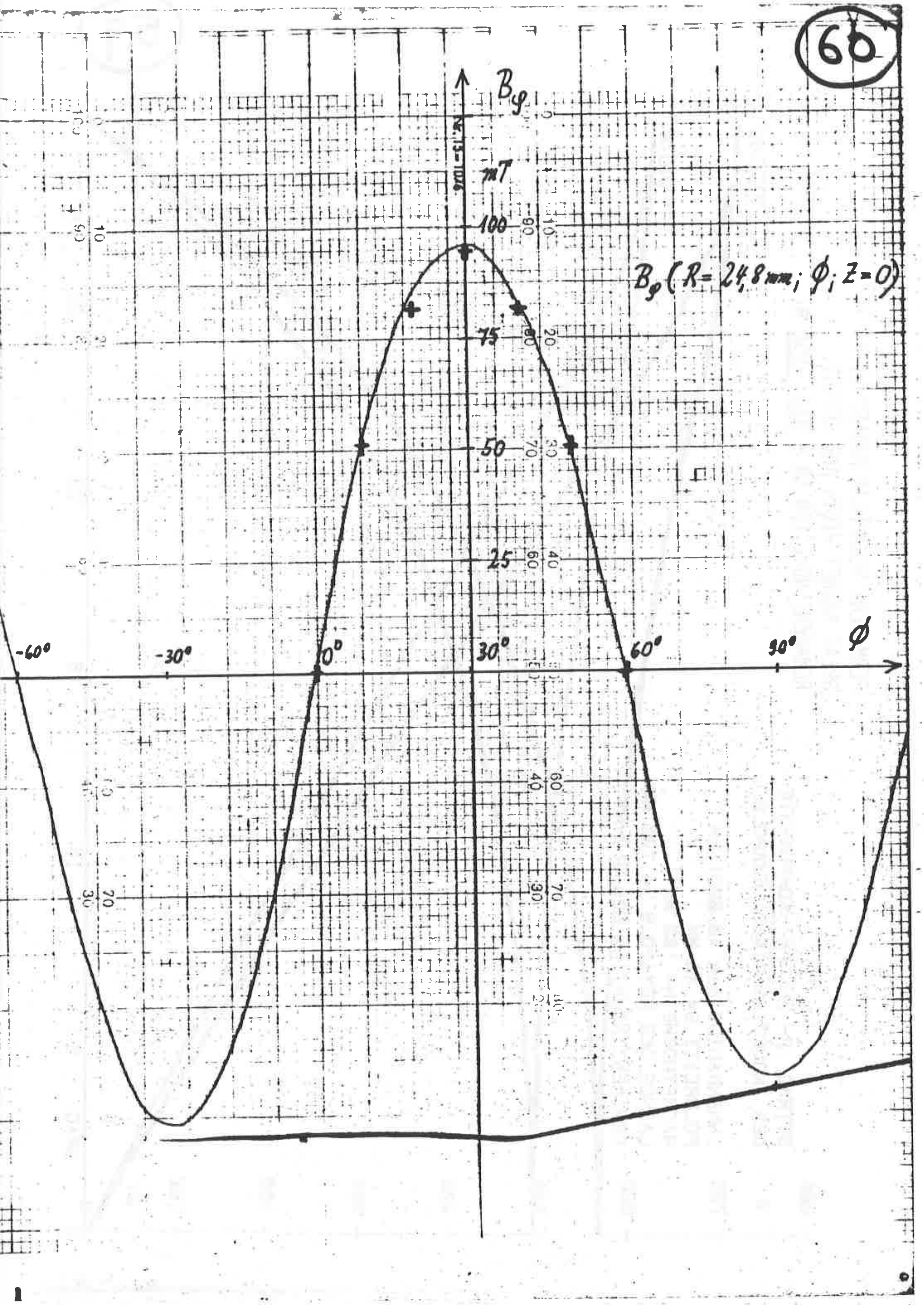

HEWLETT PACKARD
BETRAG, R- UND PHI-KOMPONENTE
DER INDUKTION EINES HEXAPOLS.
INNENRADIUS RL= 40.0001 MM
POLBREITE B= 17 MM
MAGNETHOEHE H= 42.1 MM
LAENGE DES HEXAPOLS L= 700 MM
REMANENZINDUKTION BR= 910 MT
PERMANENT HEXAPOLAR MAGNET
INDUCTION |B(Φ)|; B_r(Φ); B_φ(Φ)
WITH R = 40 mm, Z = 0 mm AND
MAGNET WIDTH B = 10; 17; 40 mm
B
800
700
600
500
400
300
200
100
MT
0
GRAD
5
10
15
20
25
PHI
30
40mm
17mm
10mm
59


BETRAG, R- UND PHI-KOMPONENTE
DER INDUKTION EINES HEXAPOLS.
INNENRADIUS RL= 40.0001 MM
POLBREITE B= 17 MM
MAGNETHOEHE H= 42.1 MM
LAENGE DES HEXAPOLS L= 700 MM
REMANENZINDUKTION BR= 910 MT
PERMANENT HEXAPOLAR MAGNET
INDUCTION |B(Φ)|; B_r(Φ); B_φ(Φ)
WITH R = 40 mm, Z = 0 mm AND
MAGNET HEIGHT H = 20; 42.1; 100 mm
B
MT
800
700
600
500
400
300
200
100
0
GRAD
5
10
15
20
25
PHI
30
H
100mm
42.1mm
20mm

58

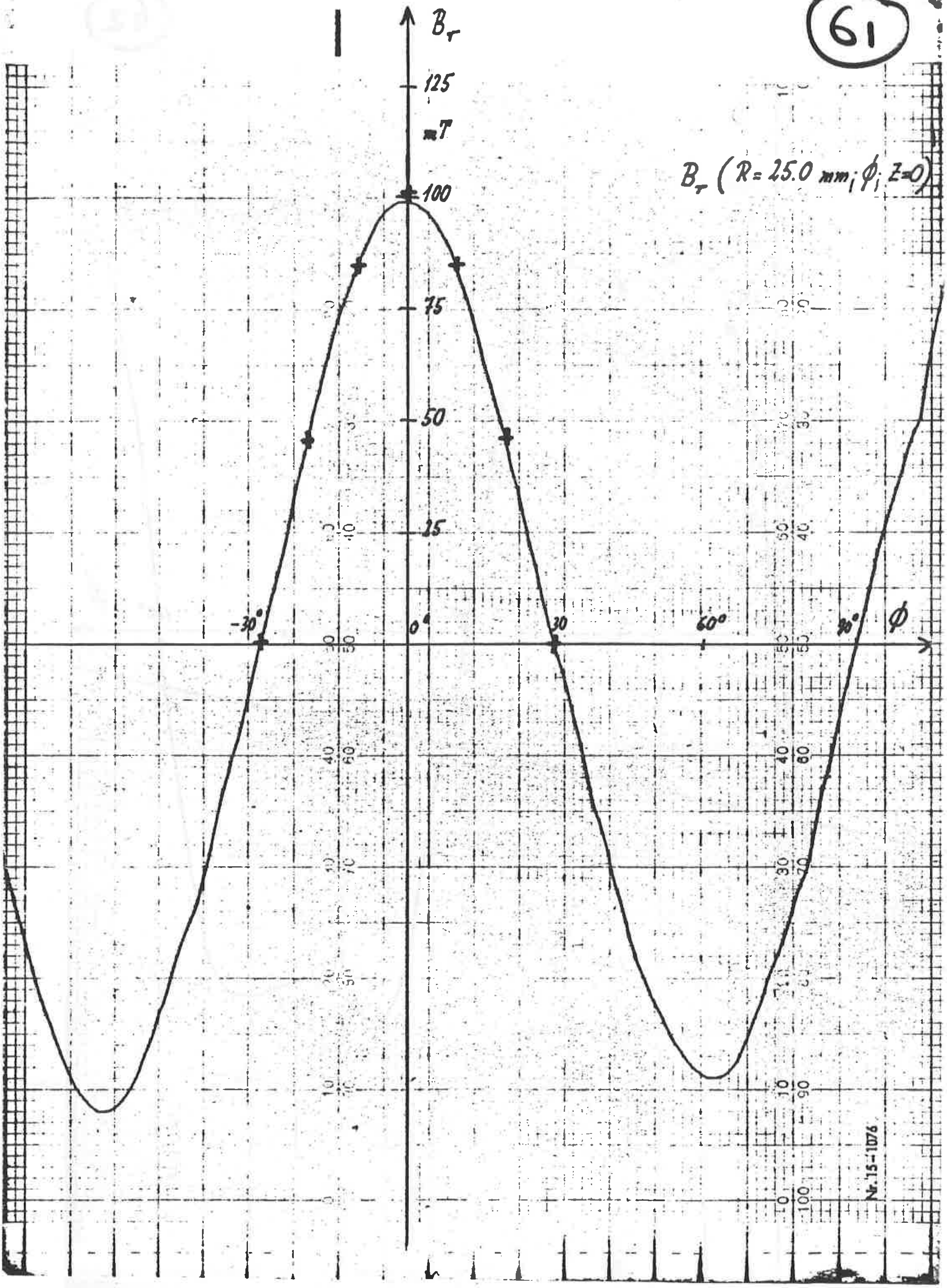
PERMANENT HEXAPOLAR MAGNET WITH
GREAT MAGNET WIDTH AND HEIGHT.
REMANENZINDUCTION BR = 910; 1050 mT.

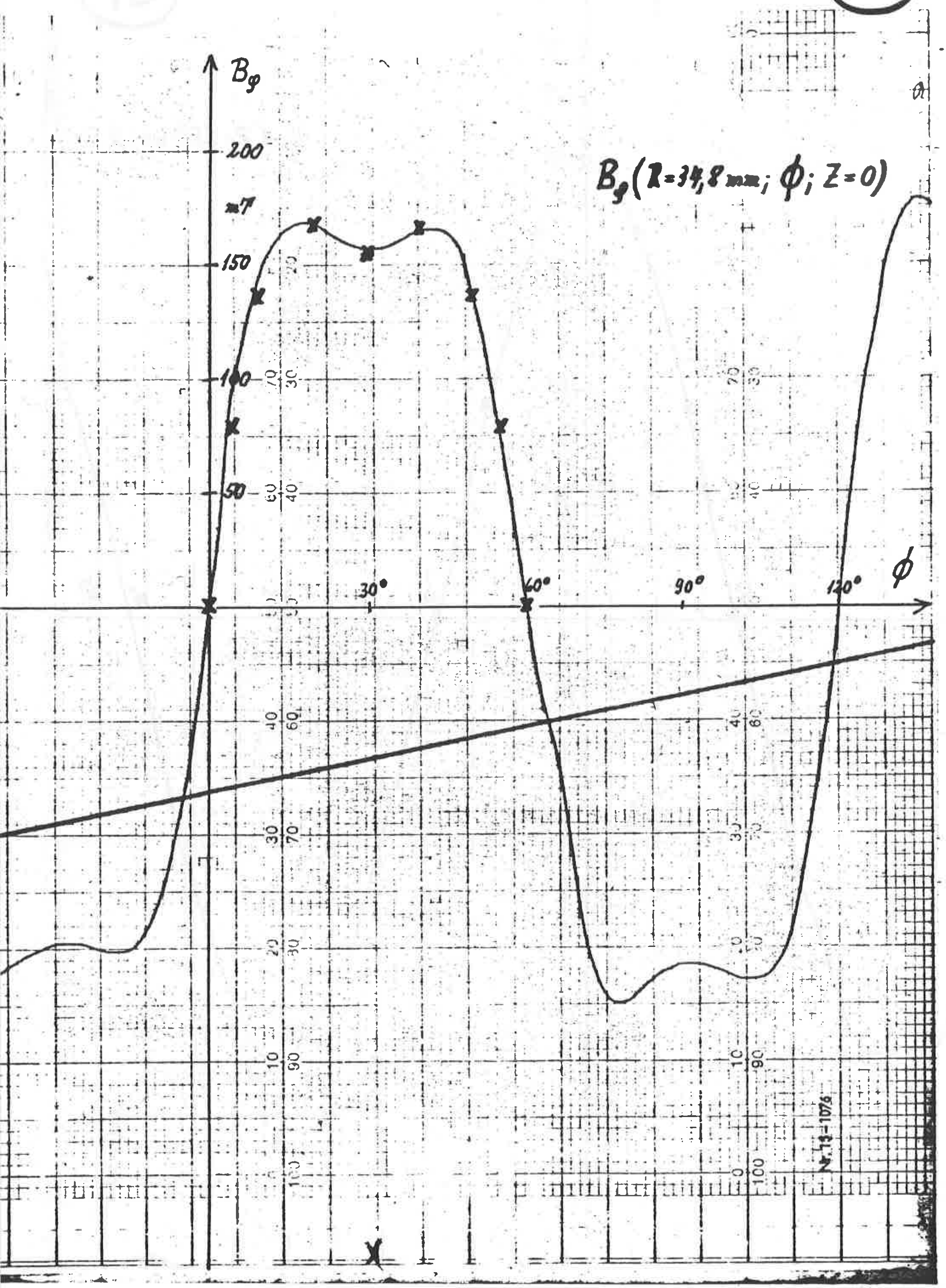




60
B_φ
mT
100
75
50
25
$B_\varphi(R = 24{,}8\,mm;\ \phi;\ z = 0)$
-60°
-30°
0°
30°
60°
90°
ϕ

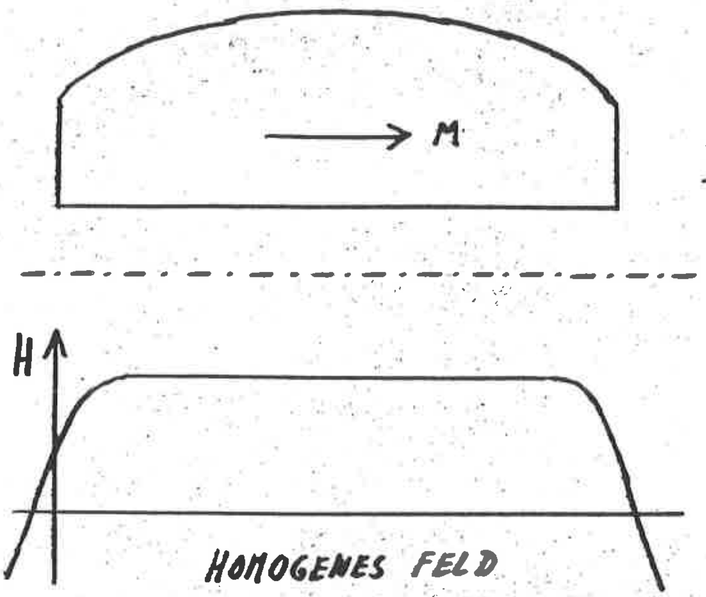
61



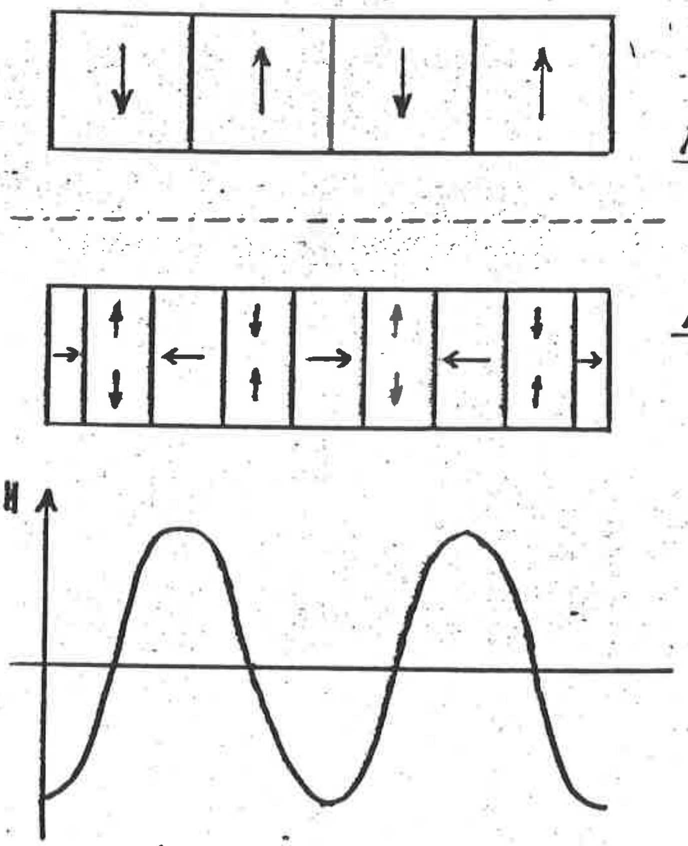


B_φ
200
mT
150
100
50
30°
60°
90°
120°
ϕ
$B_\varphi(R=34,8\,mm;\ \phi;\ Z=0)$

MAGNETSYSTEME FÜR WANDERFELDRÖHREN



TONNENMAGNET

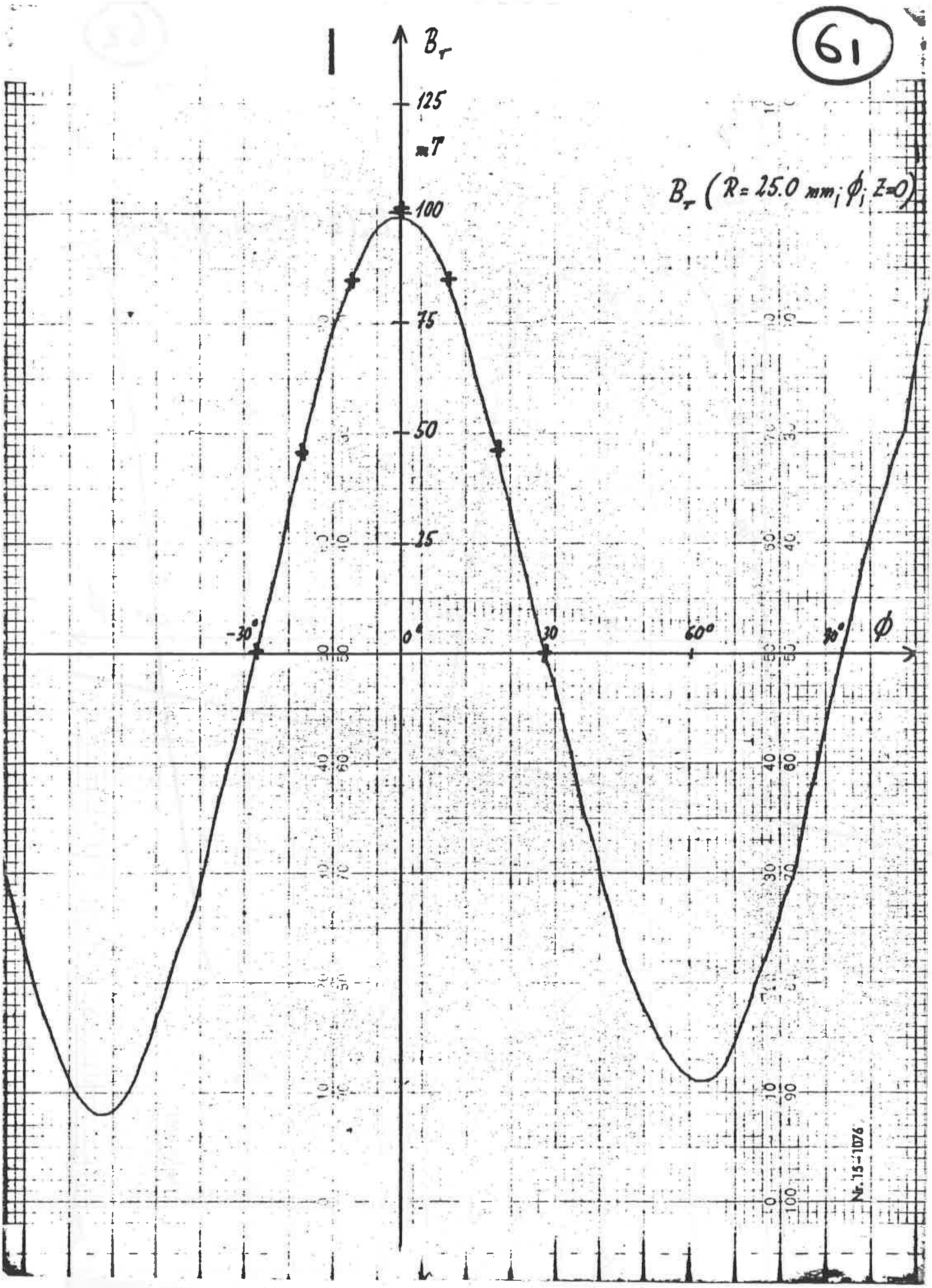


RADIAL MAGNETISIERTE

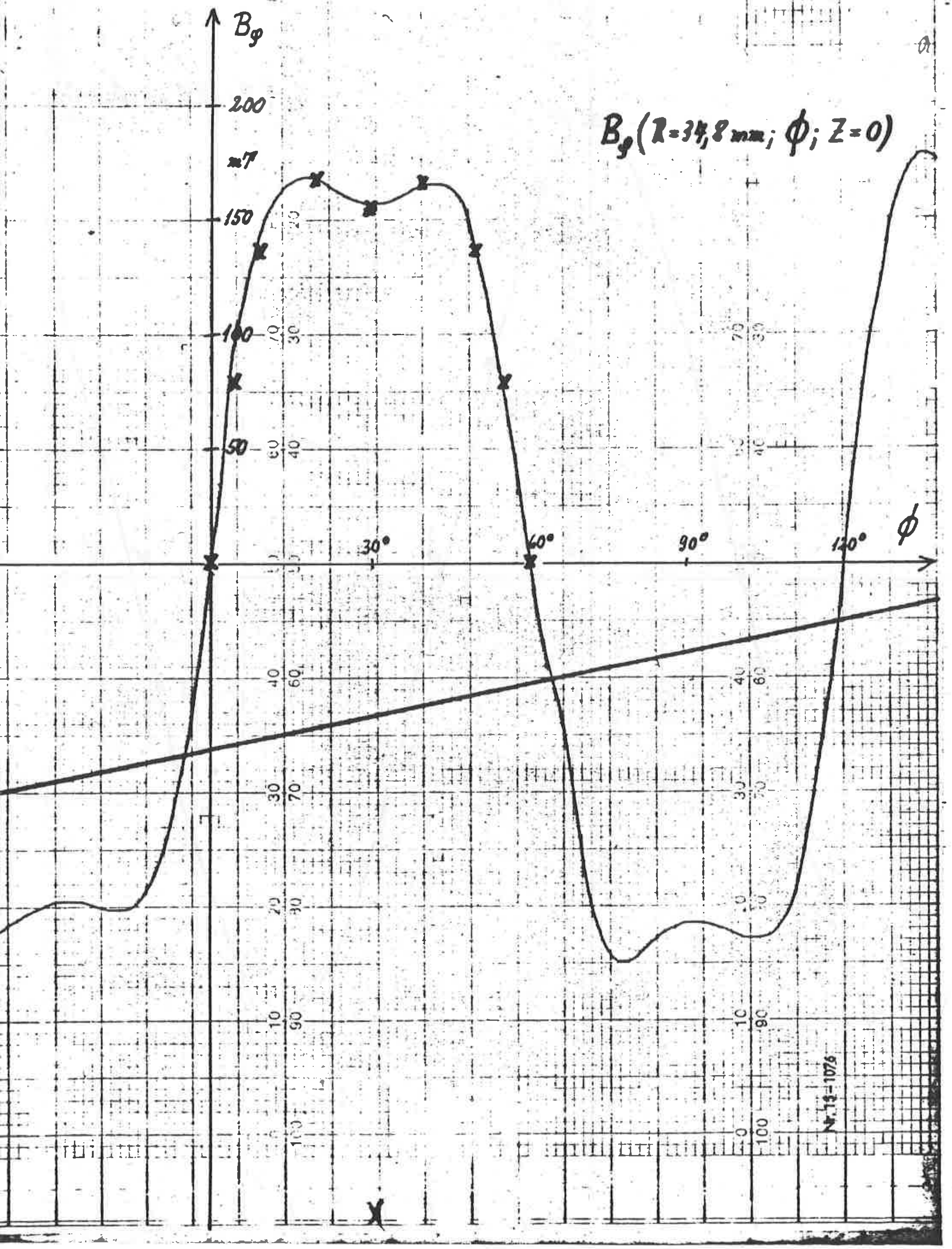
RINGE

AXIAL MAGNETISIERTE

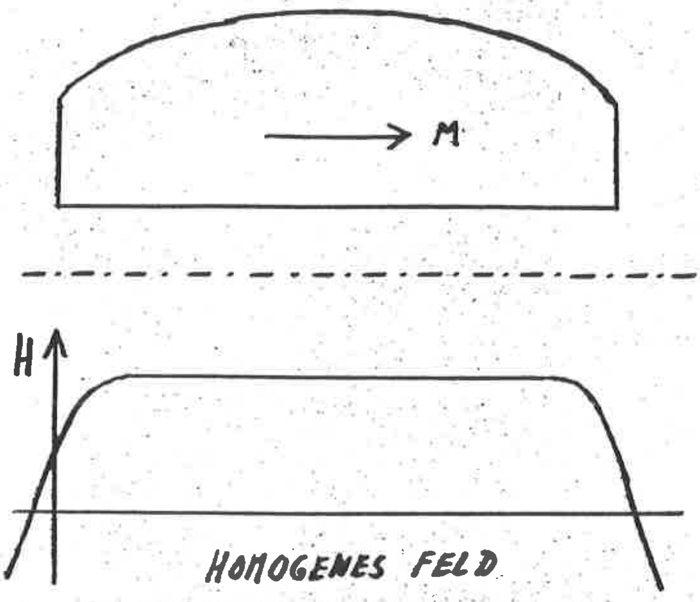
ALTERNIERENDES FELD



61
B_r
125
mT
100
75
50
25
-30°
0°
30
60°
90°
ϕ
B_r (R= 25.0 mm; ϕ; Z=0)
Nr. 15-1076

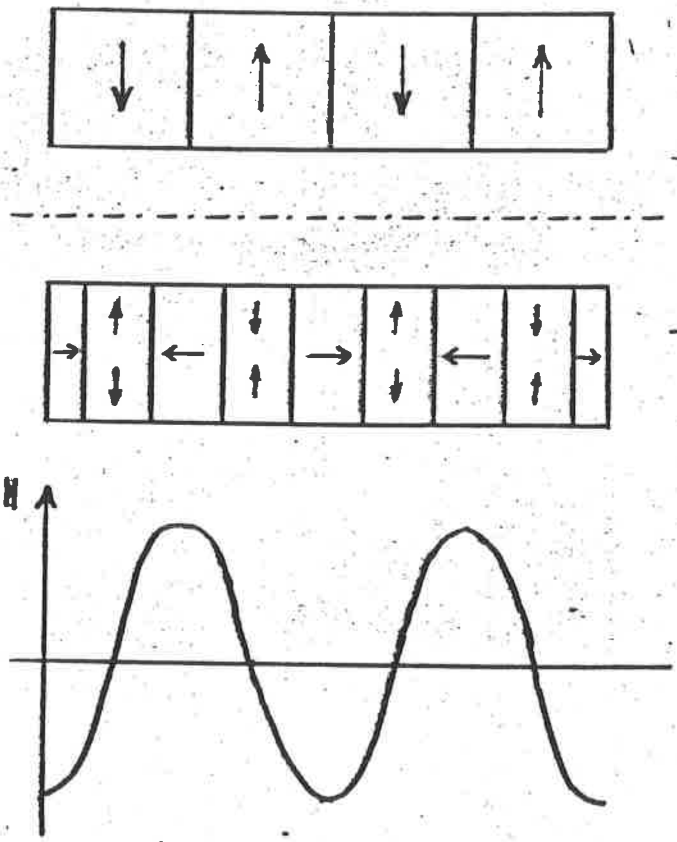

B_φ
200
mT
150
100
50
30°
60°
90°
120°
ϕ
$B_\varphi(R=34,8\ mm;\ \phi;\ Z=0)$

MAGNETSYSTEME FÜR WANDERFELDRÖHREN



TONNENMAGNET

HOMOGENES FELD



RADIAL MAGNETISIERTE

RINGE

AXIAL MAGNETISIERTE

ALTERNIERENDES FELD