JUAS 2025

Practical Activities on Magnets

Magnetic Measurements

I. Practical work on sensors and measurement techniques

Setup description

The objective of this practical work is to show practically the principles of three different field sensors:

- NMR
- Hall sensors
- Induction coils

The sensors will be tested, compared, and cross-calibrated at various field levels in a dipole magnet with an accessible aperture (C-shape).

Practical work

1) Calculation of the central and integral field of the magnet (see ANNEX)
2) Calibration exercise
    a. prepare the setup
    b. connections to the sensors to the reading instruments
    c. set a field level for the magnet
    d. take note of the reading of current, reading of NMR, voltage from Hall probe, and flux from the pickup coil
    e. repeat c) and d) for several field levels
    f. compare the results by using Excel
    g. cross-calibrate the different sensors with respect to the NMR and discuss:
        i. the range
        ii. the accuracy
        iii. the bandwidth

The students shall take note of reading of each sensor at each field level and shall create an Excel worksheet. Then, they shall retrieve the calibration coefficients by means by linear regression. The residuals shall be analysed and discussed.

II. Practical work on the rotating coil technique

Setup description

The objective of this work is to show practically the principles of a measurement of the field quality of accelerator magnets by means of rotating coils.

The setup consists of:

i) a normal-conducting quadrupole magnet (see ANNEX),
ii) a rotating coil array (shaft) with five rectangular radial coils,
iii) a motor unit connected to one end of the shaft,
iv) a angular encoder embedded into the motor unit.

The coils are connected to a patch panel. Signals from individual coils, or combinations of them, can be routed to digital integrators. The integrators compute the definite integral of the input voltage between two subsequent angular positions given by the encoder. The trigger pulses, the start and stop of the integration, are generated by a custom board connected to the encoder. The measurement process is controlled by a software application. A power converter supplies the magnets with a DC current.

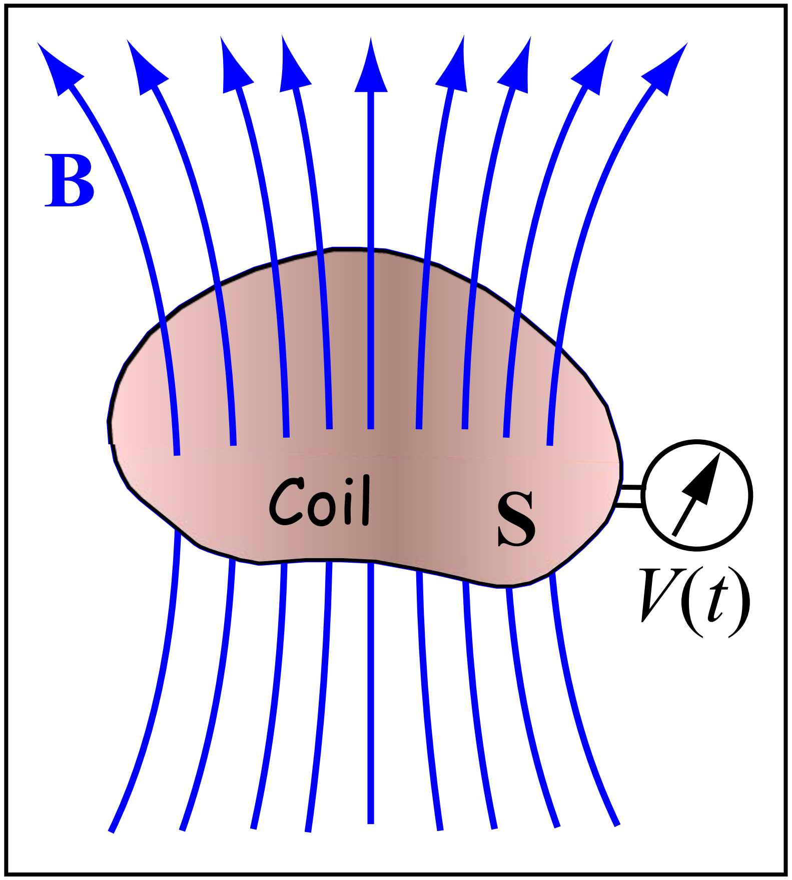
Practical work

1) Calculation of the central and integral gradient (see ANNEX)
2) Measurement exercise
    a. configuration of the system
    b. absolute and compensated signals (bucking)
    c. check of signals, noise, and bucking scheme
    d. perform a standard measurement
    e. repetition of the measurement by introduction perturbations to the field quality
3) Discussion of the results

a. transfer function, angle, magnetic center, multipoles
b. field errors and magnetic multipoles
c. allowed and not-allowed multipoles

The students should take note of the measurement results of each measurement repetition and create an Excel Worksheet. Then, they shall plot the measured multipoles and discuss the field quality of the magnet. At the end, they shall compute the changes due to the perturbations and discuss the results.

Flux Measurements



Time dependence of flux gives:

$$V(t) = -\frac{d\Phi}{dt} = -\frac{d}{dt}\left[\int_S \mathbf{B} \cdot d\,\mathbf{S}\right]$$

The change in flux is given by:

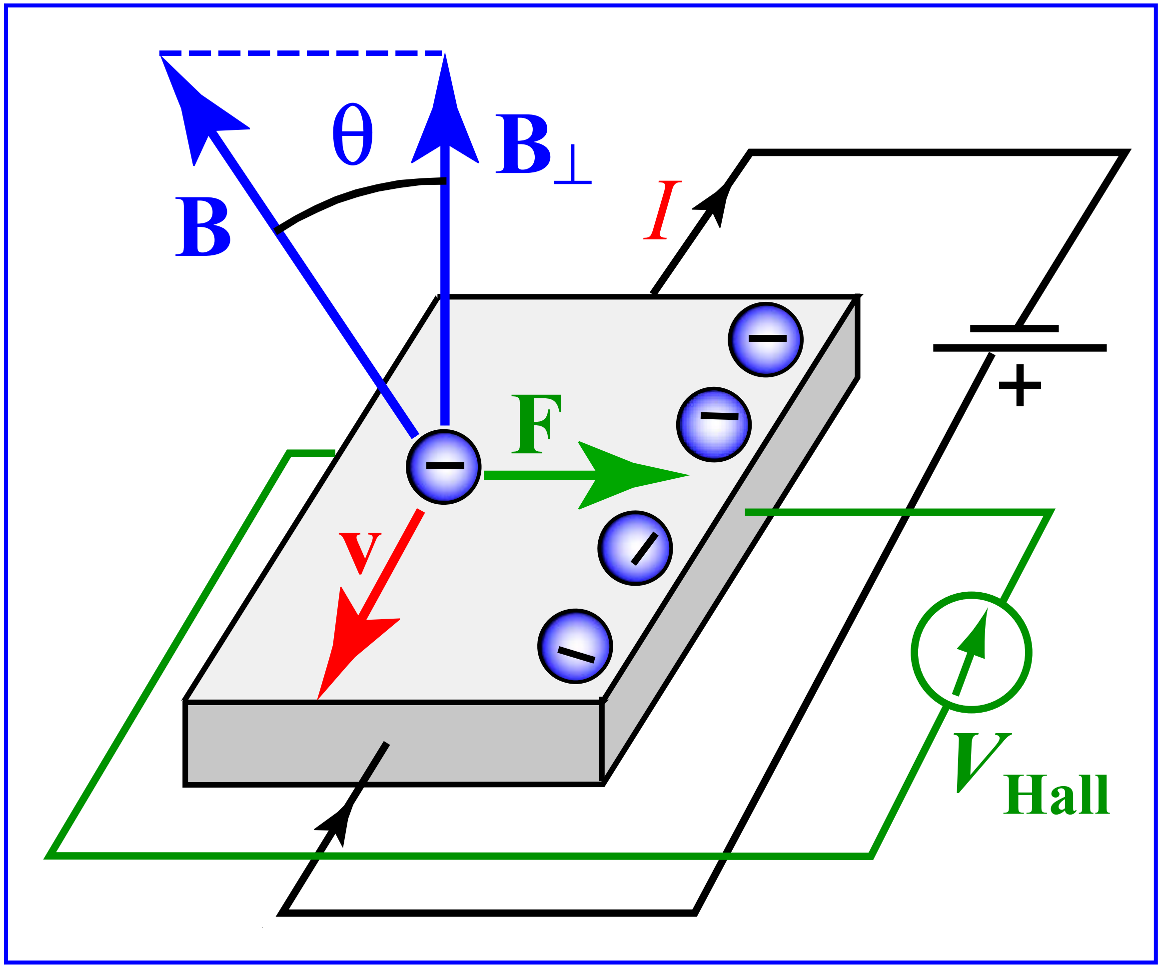
$$\Phi_{end} - \Phi_{start} = -\int_{t_{start}}^{t_{end}} V(t) \cdot dt$$

and can be measured by integrating the voltage signal.

To know the flux at a given instant, one needs to know Φ_{start}

$\Rightarrow$ (1) Use $\Phi_{start} = 0$; (2) Flip Coil/Rotating coil: $\Phi_{end} = \mp\Phi_{start}$

The Hall Effect



Charge carriers experience a **Lorentz force** in the presence of a magnetic field.

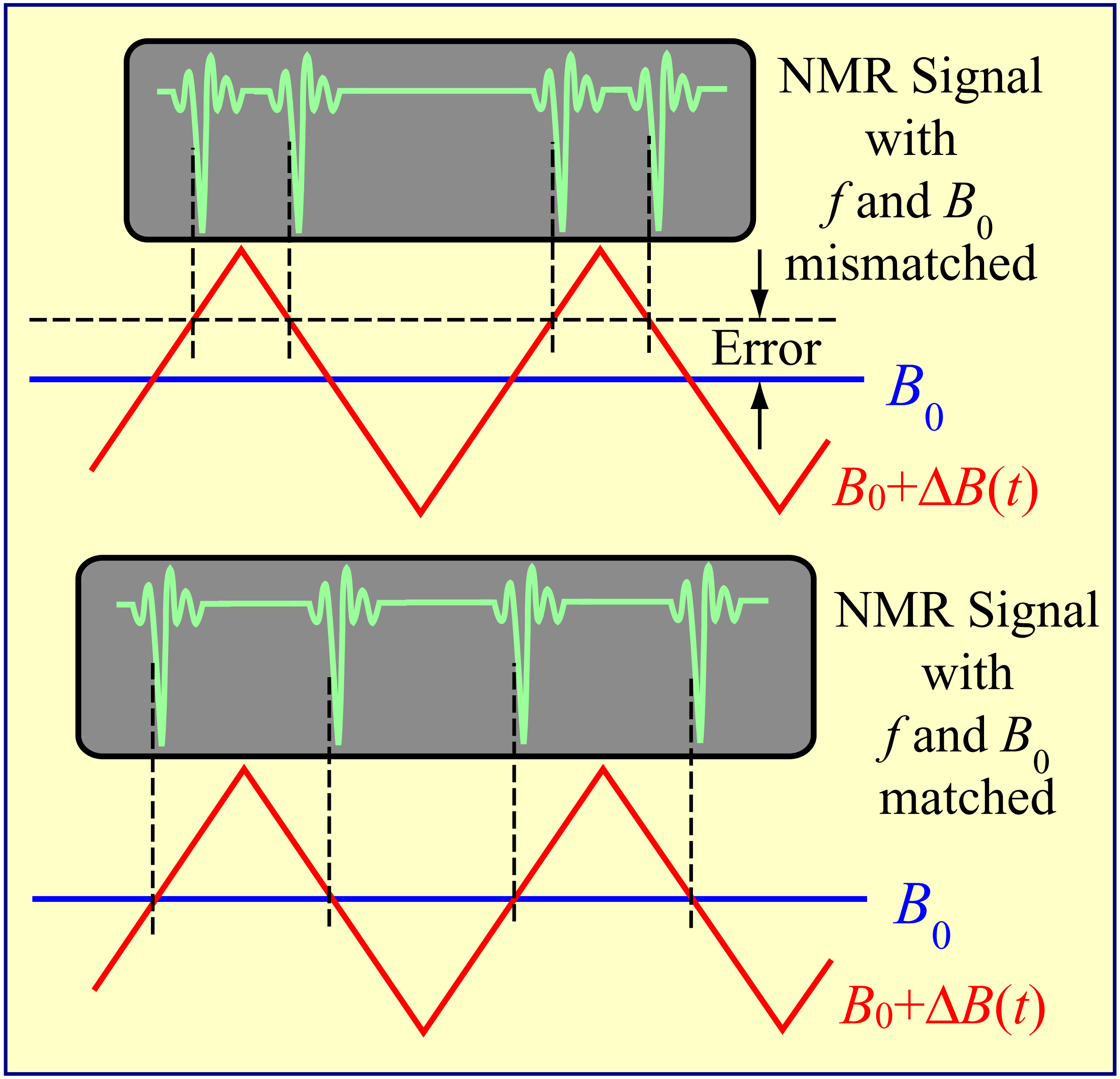
This produces a steady state voltage in a direction perpendicular to the current and field.

$$V_{\text{Hall}} = G \cdot R_H \cdot I \cdot B \cos\theta$$

G = Geometric factor

R_H = Hall Coefficient

Locking RF to NMR Resonance



Resonance occurs at non-zero value of modulating signal.

NMR signals arrive at uneven intervals.

Resonance occurs at Zero value of modulating signal.

NMR signals arrive at even intervals.

TYPE: HHP-NPs	PRODUCT NUMBER:

PARAMETER	UNIT	297 K	77 K	4.2 K
Nominal control current, I_n	mA	20	20	20
Maximum control current	mA	25	30	30
Sensitivity at I_n (1)	mV/T	218.0	*222.8*	*223.6*
Offset voltage at I_n	μV	74	682	
Input resistance	Ω	9	8	
Output resistance	Ω	28	23	
Linearity error up to 1 T	%	< 0.2		
Change of sensitivity due to reversing of the magnetic field	%	< 1		
Operating temperature range	K	1.5 - 330		
Active area dimension	μm	500 x 100		
Overall dimension (w x l x h)	mm	5 x 7 x 1.8		
Wires length	mm	150		

(1) *Sensitivity of uncalibrated Hall probe at temperature 77 K and 4.2 K is calculated from the sensitivity value measured at 297 K.*

COLOR CODE:

Control current leads: +green, black

Hall leads: +red, orange

Excitation current in a dipole

Ampere's law $\oint \vec{H} \cdot d\vec{l} = NI$ and $\vec{B} = \mu\vec{H}$ with $\mu = \mu_0 \mu_r$

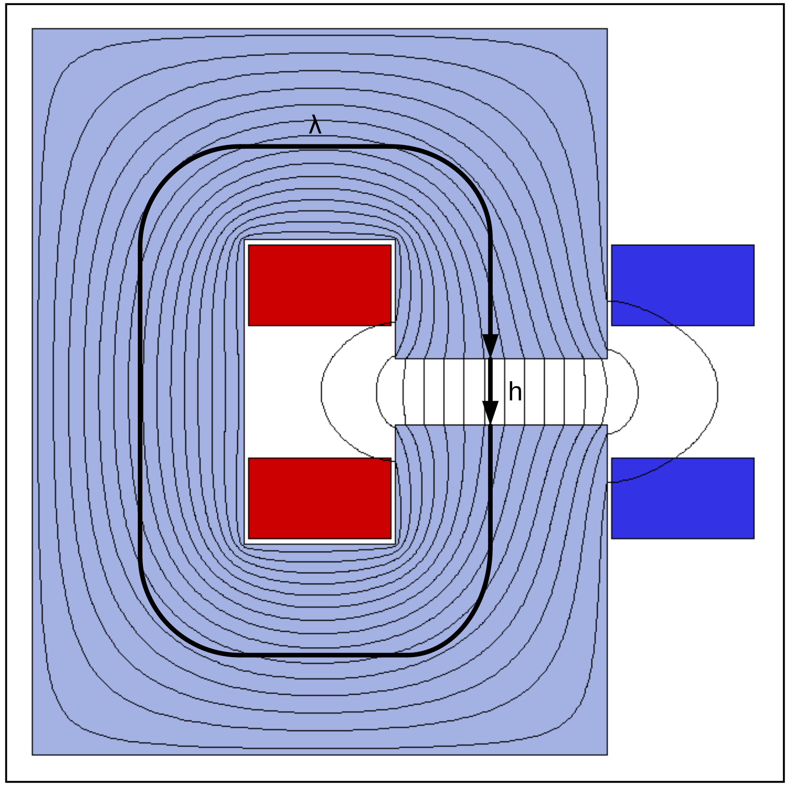
leads to $$NI = \oint \frac{\vec{B}}{\mu} \cdot d\vec{l} = \int_{gap} \frac{\vec{B}}{\mu_{air}} \cdot d\vec{l} + \int_{yoke} \frac{\vec{B}}{\mu_{iron}} \cdot d\vec{l} = \frac{Bh}{\mu_{air}} + \frac{B\lambda}{\mu_{iron}}$$

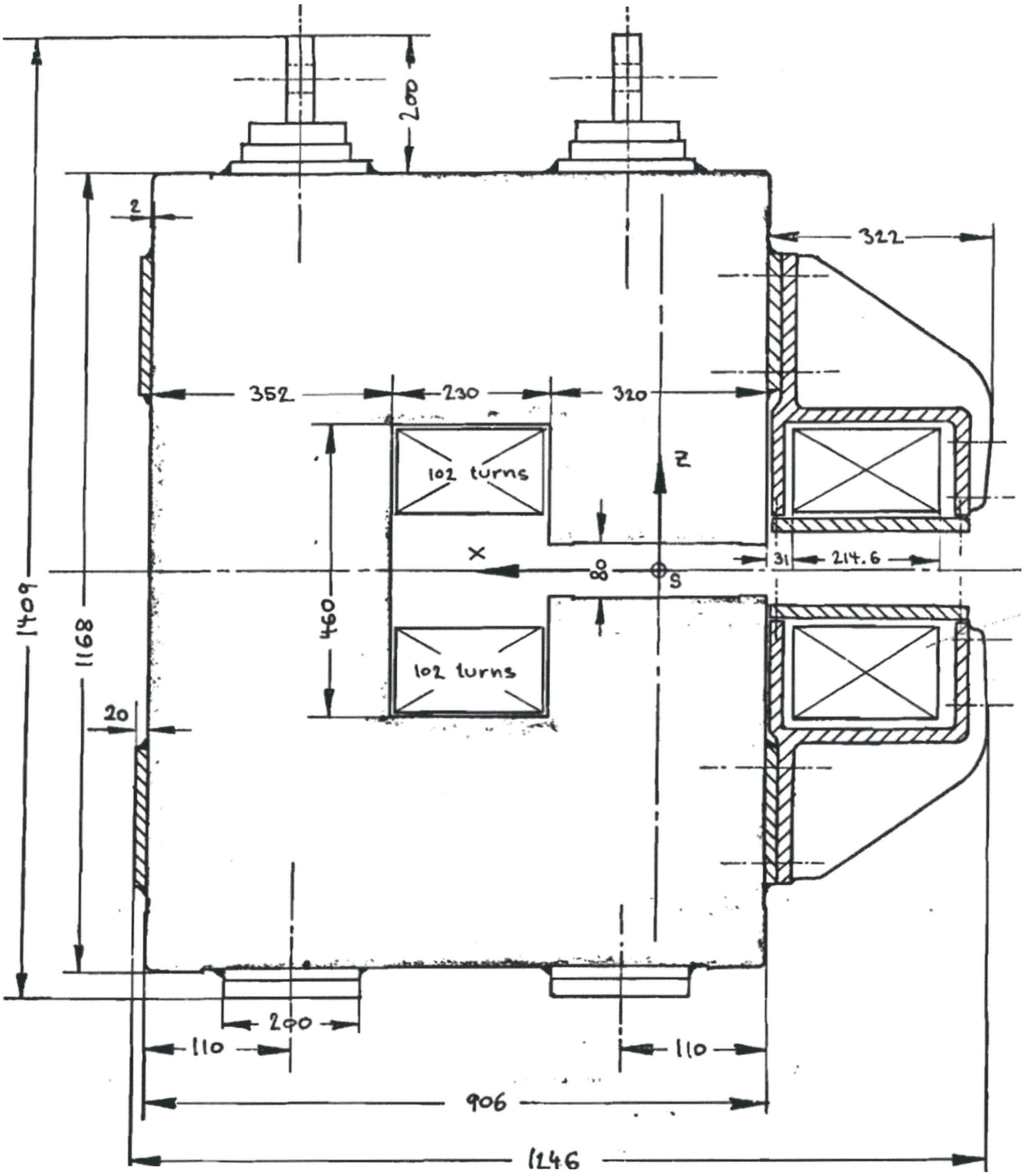
assuming, that *B* is constant along the path

If the iron is not saturated: $$\frac{h}{\mu_{air}} \gg \frac{\lambda}{\mu_{iron}}$$

then: $$NI_{(perpole)} \approx \frac{Bh}{2\mu_0}$$

h: gap height [m]





200
2
322
352
230
320
Z
102 turns
X
80
S
31
214.6
460
1409
1168
20
102 turns
200
110
110
906
1246

Excitation current in a Quadrupole

Choosing the shown integration path gives: $NI = \oint \vec{H} \cdot \vec{dl} = \int_{s1} \overrightarrow{H_1} \cdot \vec{dl} + \int_{s2} \overrightarrow{H_3} \cdot \vec{dl} + \int_{s3} \overrightarrow{H_3} \cdot \vec{dl}$

For a quadrupole, the gradient $B' = \frac{dB}{dr}$ is constant

and $B_y = B'x \qquad B_x = B'y$

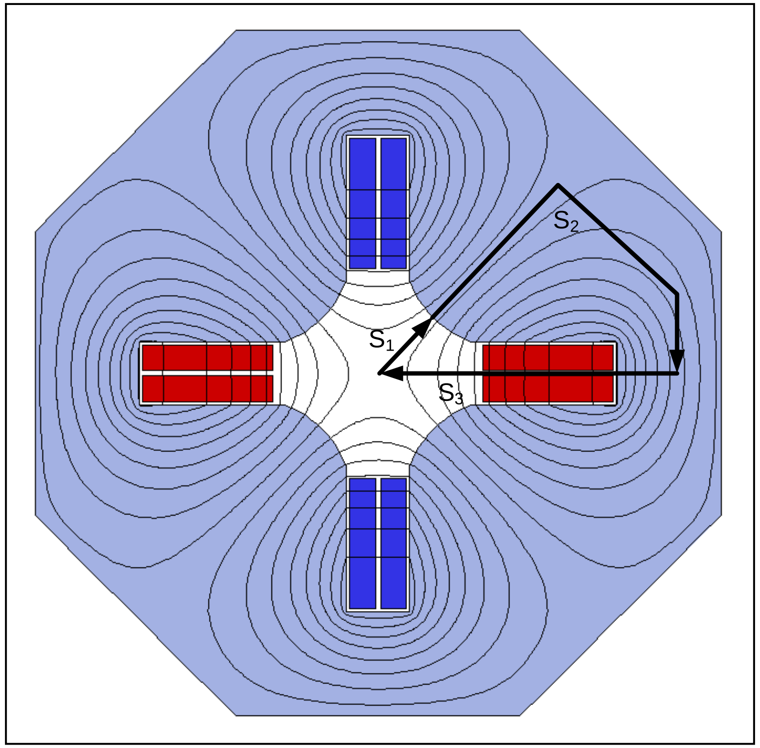
Field <u>modulus</u> along s_1: $H(r) = \sqrt{H_x^2 + H_y^2} = \frac{B'}{\mu_0}\sqrt{x^2 + y^2} = \frac{B'}{\mu_0} r$

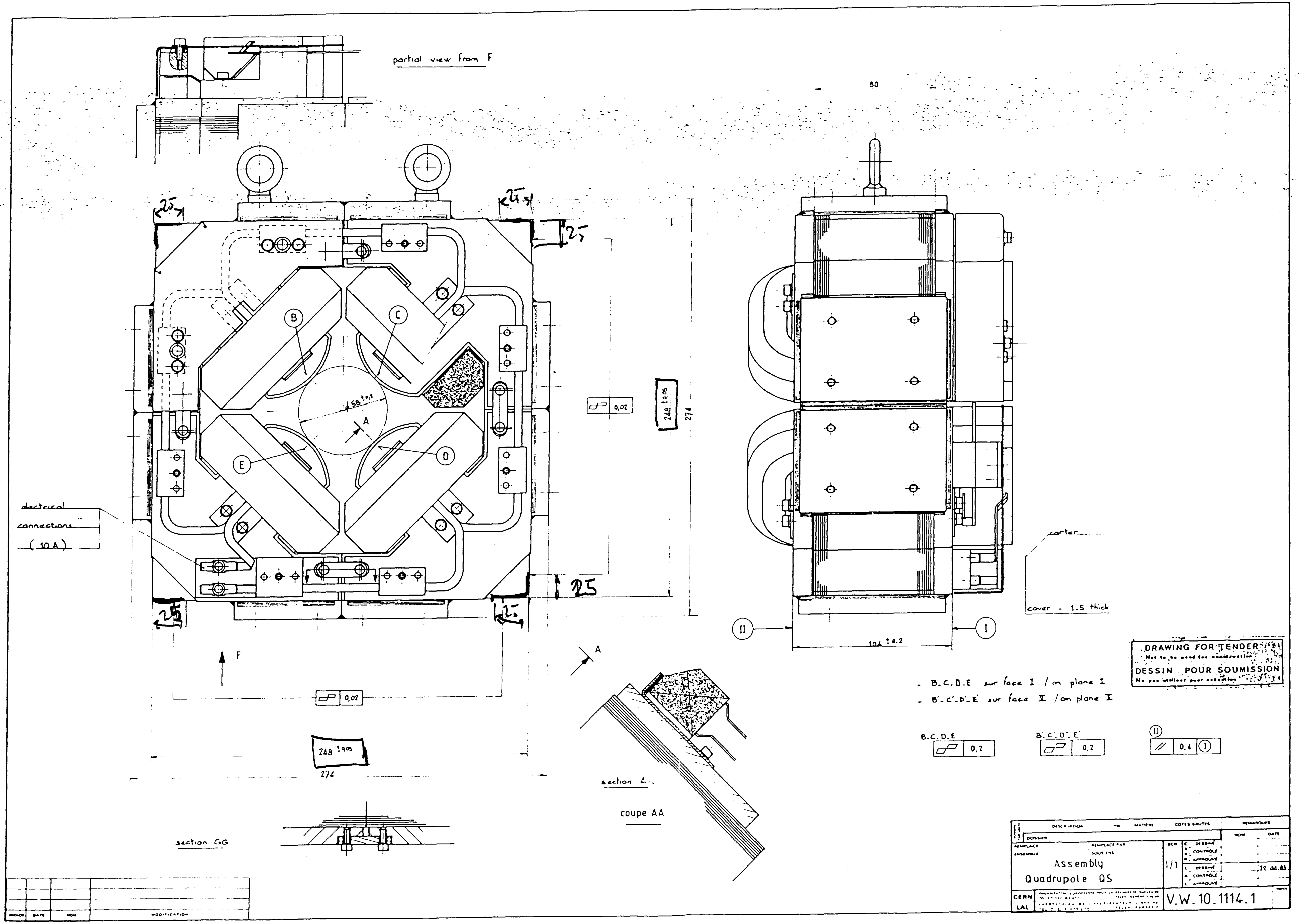
Neglecting H in s_2 because: $R_{M,s2} = \frac{s_2}{\mu_{iron}} << \frac{s_1}{\mu_{air}}$

and along s_3: $\int_{s3} \overrightarrow{H_3} \cdot \vec{dl} = 0$

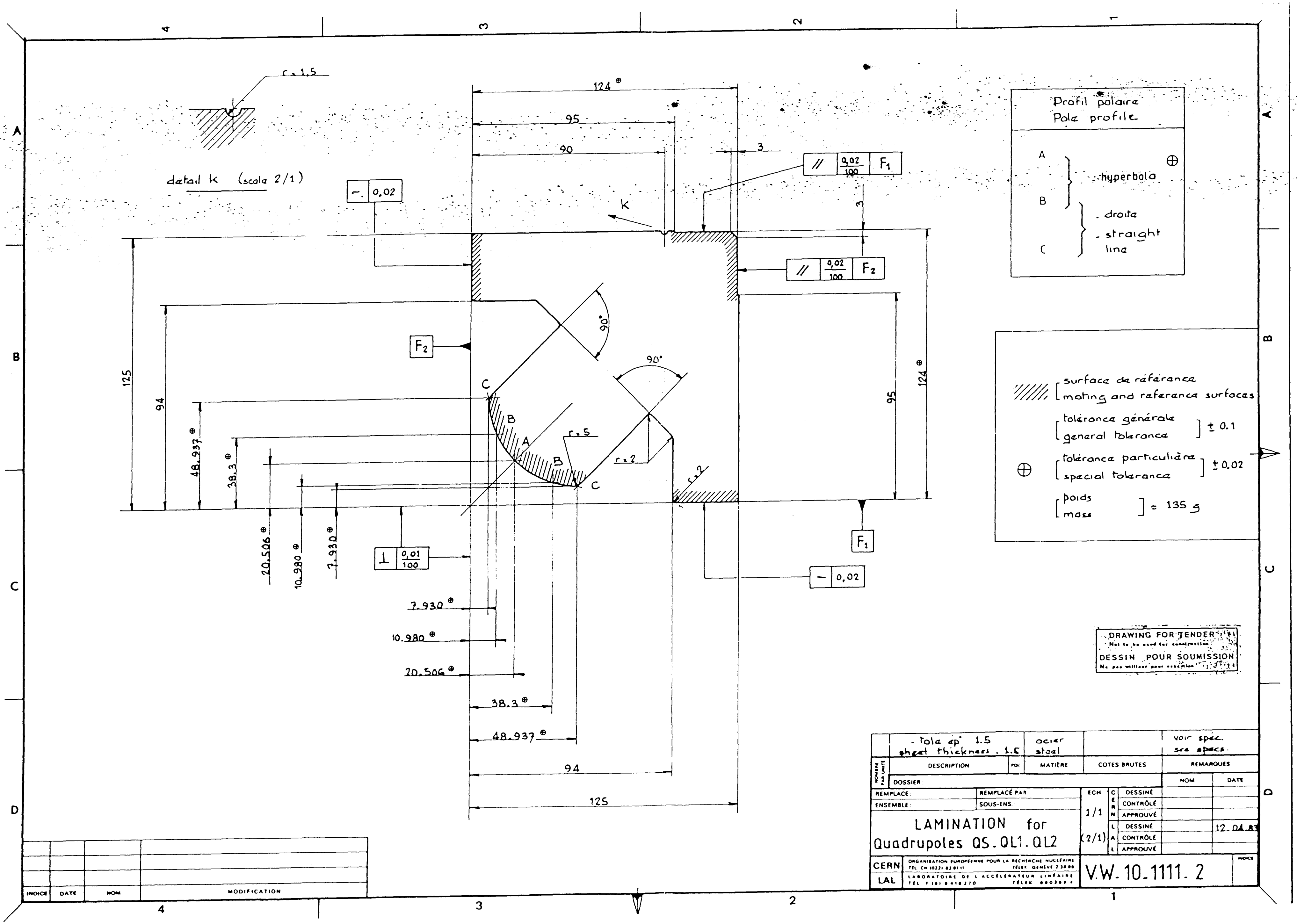
Leads to: $NI \approx \int_0^R H(r)dr = \frac{B'}{\mu_0}\int_0^R r \cdot dr$

$$NI_{(per\ pole)} = \frac{B'r^2}{2\mu_0}$$





partial view from F
80
electrical connections
(10 A)
B
C
D
E
A
F
25
0,02
248 ±0,05
274
272
104 ± 0.2
I
II
carter
cover - 1.5 thick
DRAWING FOR TENDER
Not to be used for construction
DESSIN POUR SOUMISSION
Ne pas utiliser pour exécution
- B.C.D.E sur face I / on plane I
- B'.C'.D'.E' sur face II / on plane II
B.C.D.E 0,2
B'.C'.D'.E' 0,2
// 0,4 I
section A
coupe AA
section GG
MODIFICATION
DESCRIPTION
MATIERE
COTES BRUTES
REMARQUES
DOSSIER
REMPLACE
REMPLACE PAR
ENSEMBLE
SOUS ENS
Assembly
Quadrupole QS
ECH
1/1
DESSINÉ
CONTROLÉ
APPROUVÉ
NOM
DATE
22.04.83
CERN
LAL
V.W. 10. 1114. 1



r = 1.5
detail K (scale 2/1)
124 ⊕
95
90
3
// 0,02/100 F1
// 0,02/100 F2
⌒ 0,02
— 0,02
⊥ 0,01/100
K
F1
F2
90°
90°
C
B
A
B
C
r = 5
r = 2
r = 2
125
94
48.937 ⊕
38.3 ⊕
20.506 ⊕
10.980 ⊕
7.930 ⊕
7.930 ⊕
10.980 ⊕
20.506 ⊕
38.3 ⊕
48.937 ⊕
94
125
95
124 ⊕
Profil polaire
Pole profile
A
B
C
hyperbola
droite
straight line
⊕
surface de référence
mating and reference surfaces
tolérance générale
general tolerance
± 0.1
tolérance particulière
special tolerance
± 0.02
poids
mass
= 135 g
DRAWING FOR TENDER
Not to be used for construction
DESSIN POUR SOUMISSION
Ne pas utiliser pour exécution
- tole ép. 1.5
sheet thickness 1.5
acier
steel
voir spec.
see specs.
DESCRIPTION
MATIÈRE
COTES BRUTES
REMARQUES
DOSSIER
NOM
DATE
REMPLACE
REMPLACÉ PAR
ENSEMBLE
SOUS-ENS.
ECH.
1/1
(2/1)
DESSINÉ
CONTRÔLÉ
APPROUVÉ
12.04.83
LAMINATION for
Quadrupoles QS.QL1.QL2
CERN
LAL
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE
V.W. 10.1111. 2
INDICE
DATE
NOM
MODIFICATION

TABLE I

Summary of relevant parameters

	QS	QL1	QL2	
1 NOMINAL OPERATING PARAMETERS				
Magnetic gradient	2.5	2.5	5.6	T/m
Power consumption at 35 deg C	36	53	564	W
2 DIMENSIONS AND MASS				
Maximum overall length	175	270	270	mm
Maximum width	274	274	274	mm
Approximate total mass	51	94	86	kg
3 MAGNETIC CIRCUIT				
Inscribed circle diameter	58	58	58	mm
Pole shape (see Table II)	hyperbolic in central region			
Lamination thickness	1.5	1.5	1.5	mm
Punching precision	±0.02	±0.02	±0.02	mm
Stack length (incl. end-plates)	104.0±.2	200.0±.2	200.0±.2	mm
Packing factor	≥ 0.95	≥ 0.95	≥ 0.95	
Mass of steel laminations	28	61	61	kg
4 EXCITATION COILS				
Number of windings/coil	85	85	19	
Conductor section	5 x 1.6	5 x 1.6	4.5 x 4.5	mm^2
Cooling channel dia.	no	no	2.5	mm
Conductor length/coil	36	52	11.8	m
Excitation current	10	10	100	A
Overall length of coil	175	270	270	mm
Resistance/coil at 20 deg C	85	124	13.8	mOhm
Mass of copper/coil	2.4	3.5	1.6	kg
5 HYDRAULIC CIRCUIT				
Number of coils in series			4	
Test pressure			25	bar
Nominal pressure drop			6	bar
Maximum water pressure			8	bar
Nominal cooling water flow			23	lit/h
Nominal temperature rise			21	deg C