Magnetisme

- **Magnetostatikk** (ingen tidsvariasjon):
- Kap 27. Magnetiske krefter
- Kap 28: Magnetiske kilder
- **Elektrodynamikk:**
- Kap 29-32:

  Tidsvariasjon: Induksjon mm.

Kap 28: Magnetiske kilder

- **Elektrostatikk:**

  Ladning *q* påvirkes av kraft *q**E*** (Coulombs lov)

  → Definisjon *E*-felt

  E-feltet skapes fra ladninger (Coulombs lov)

- **Magnetostatikk:**

  Ladning *q* **i bevegelse** påvirkes av kraft *q**v*** x ***B***

  → Definisjon *B*-felt (Lorentzkrafta)

  B-feltet skapes fra ladninger **i bevegelse**

  (Biot-Savarts lov)

- **Hjelpelover:**

  Elektrostatikk: Gauss' lov

  Magnetostatikk: Amperes lov

- **Magnetiske materialer**

  Ferromagnetisk materiale. Magnetisering. ***M***-vektor og ***H***-vektor.

Kap 28: Magnetiske kilder

28.1 *B*-felt fra **enkeltladninger** i bevegelse

28.2 *B*-felt fra **strøm** i ledning

28.1+28.2 Bevegelse av ladninger gir magnetfelt *B*

- Enkeltladning i bevegelse:

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \qquad (28.2)$$

Enhetsvektor

$$= \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\vec{r}}{r^3}$$

- Strøm i leder: (Biot-Savarts lov)

$$\mathrm{d}\vec{B} = \frac{\mu_0}{4\pi}\frac{I\mathrm{d}\vec{s}\times\hat{r}}{r^2}$$

Enhetsvektor

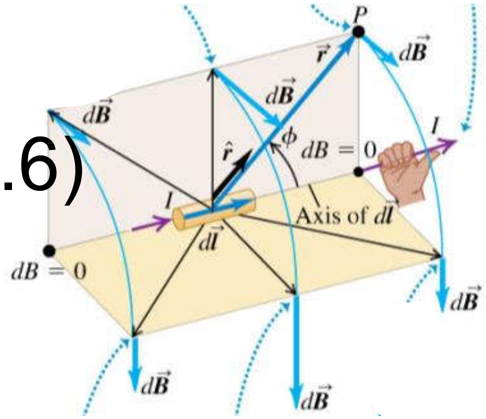
$$= \frac{\mu_0}{4\pi}\frac{I\mathrm{d}\vec{s}\times\vec{r}}{r^3} \qquad (28.6)$$

1819-25: Vitenskapelig arbeid:
Hans Christian Ørsted, André Ampere,
Jean-Baptist Biot, Felix Savart,
Michael Faraday, Joseph Henry

28.1+28.2 Bevegelse av ladninger gir magnetfelt *B*

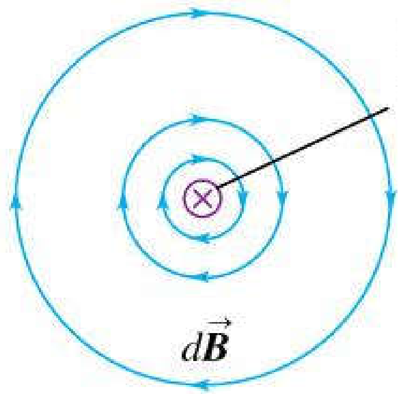
- Enkeltladning: $$\vec{B} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2} \quad (28.2)$$

- Strømelement: $$d\vec{B} = \frac{\mu_0}{4\pi} \frac{I\,d\vec{s} \times \hat{r}}{r^2} \quad (28.6)$$



- Strøm i leder: $$d\vec{B} = \frac{\mu_0 I}{4\pi} \int_{\text{ledning}} \frac{d\vec{s} \times \hat{r}}{r^2} \quad (28.7)$$

  (Biot-Savarts lov)



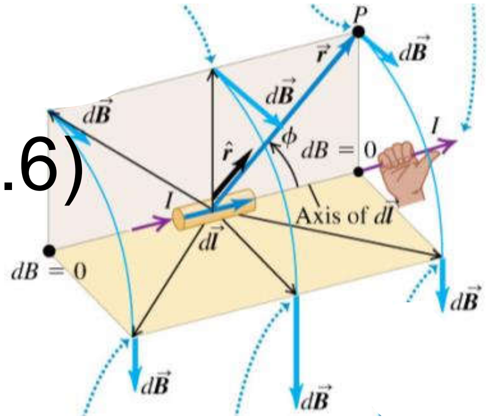
Elmag og relativitetsteori i Notat 3

Einsteins utledning av spesiell relativitetsteori var drevet av dette problemet i elektromagnetismen:

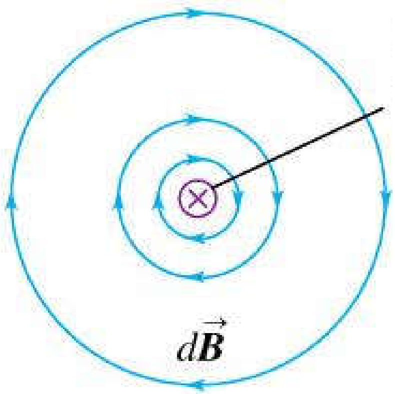
Elektriske og magnetiske krefter er to sider av samme sak, avhengig av referansesystemet det hele observeres i.

28.1+28.2 Bevegelse av ladninger gir magnetfelt *B*

- Enkeltladning: $$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2} \quad (28.2)$$
- Strømelement: $$\mathrm{d}\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,\mathrm{d}\vec{s}\times\hat{r}}{r^2} \quad (28.6)$$

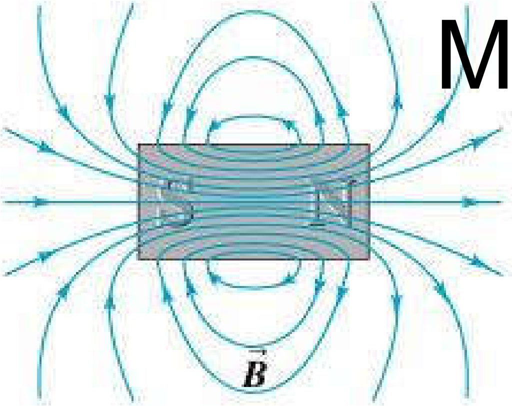


- Strøm i leder: (Biot-Savarts lov) $$\mathrm{d}\vec{B} = \frac{\mu_0 I}{4\pi}\int_{\text{ledning}}\frac{\mathrm{d}\vec{s}\times\hat{r}}{r^2} \quad (28.7)$$

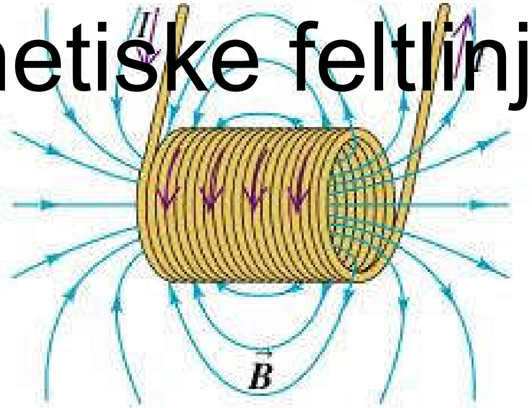


(Fig 27.11)

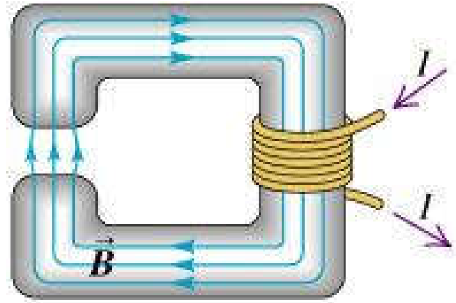
Magnetiske feltlinjer



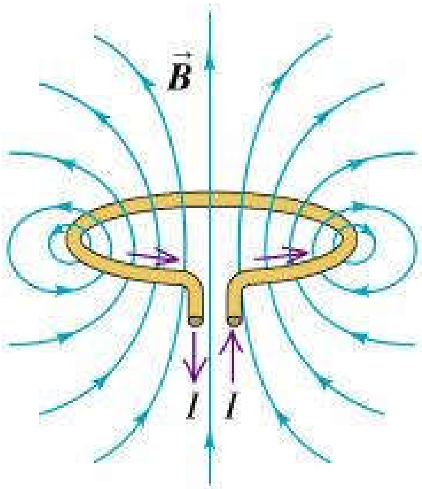
(a) Magnetic field lines through the center of a permanent magnet



(b) Magnetic field lines through the center of a cylindrical current-carrying coil

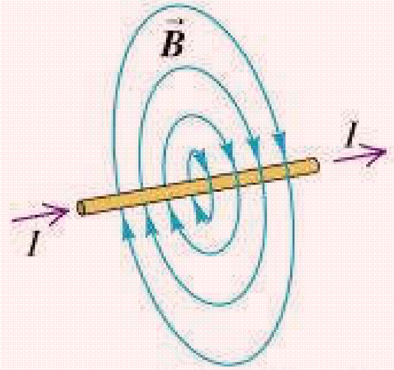


(c) Magnetic field lines through the center of an iron-core electromagnet

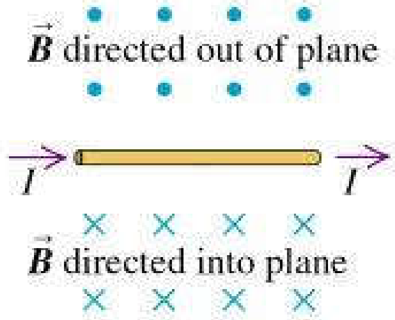


(d) Magnetic field lines in a plane containing the axis of a circular current-carrying loop

Eks. 1

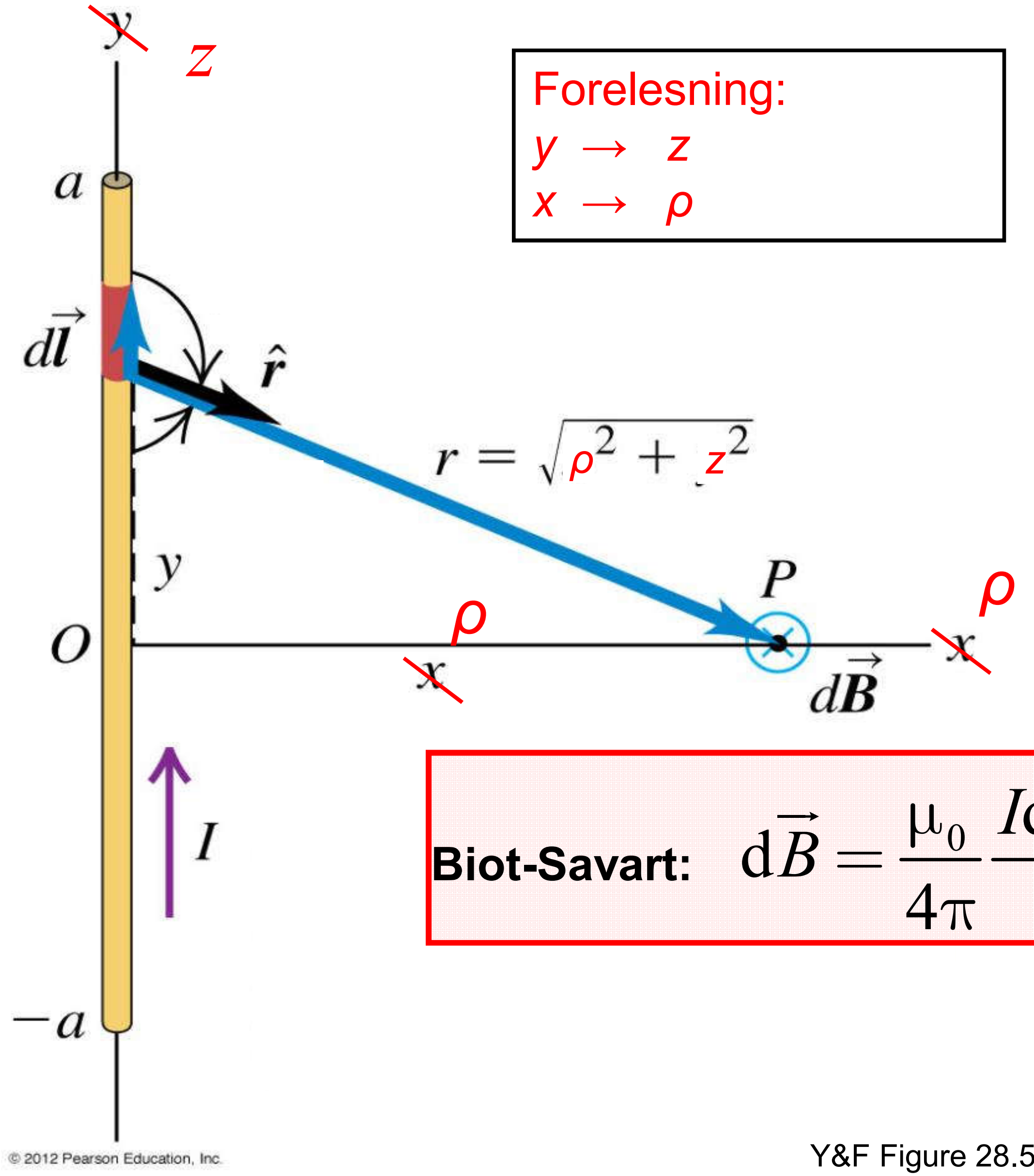


(e) Magnetic field lines in a plane perpendicular to a long, straight, current-carrying wire



(f) Magnetic field lines in a plane containing a long, straight, current-carrying wire

Eks. 1 (Y&F Kap. 28.3):
B-felt på midtnormal til rett leder, lengde 2*a*



Forelesning:
$y \rightarrow z$
$x \rightarrow \rho$

Biot-Savart: $$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I d\vec{s} \times \vec{r}}{r^3}$$

Y&F Figure 28.5

Rottmann integraltabell (s. 137)

47) $$^*\int \frac{x}{X^{3/2}}\,dx = \frac{-1}{ac-b^2}\,\frac{bx+c}{\sqrt{X}} + C$$

48) $$^*\int \frac{dx}{X^{3/2}} = \frac{1}{ac-b^2}\,\frac{ax+b}{\sqrt{X}} + C$$

49) $$\int x(ax^2+c)^{k+1/2}dx = \frac{1}{(2k+3)a}(ax^2+c)^{k+3/2} + C, \quad k \neq -\frac{3}{2}$$

50) $$\int \frac{dx}{x\sqrt{ax^2+c}} = \begin{cases} \dfrac{-1}{\sqrt{c}} \ln C_1 \dfrac{\sqrt{c}+\sqrt{ax^2+c}}{x}, \text{ for } c > 0; \\ \dfrac{-1}{\sqrt{-c}} \arcsin\sqrt{\dfrac{-c}{a}}\,\dfrac{1}{|x|} + C_2, \\ \text{for } c < 0 \text{ og } |x| \geq \sqrt{\dfrac{-c}{a}} \end{cases}$$

---

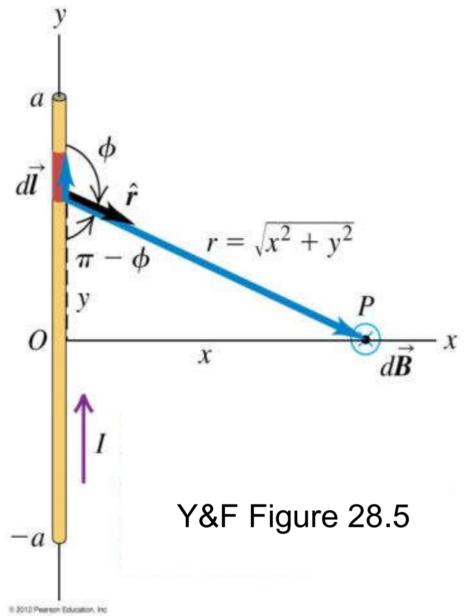
*) $X = ax^2 + 2bx + c$

$X = z^2 + \rho^2$, dvs:

$x = z$
$a = 1$
$b = 0$
$c = \rho^2$

Rett leder lengde $2a$:

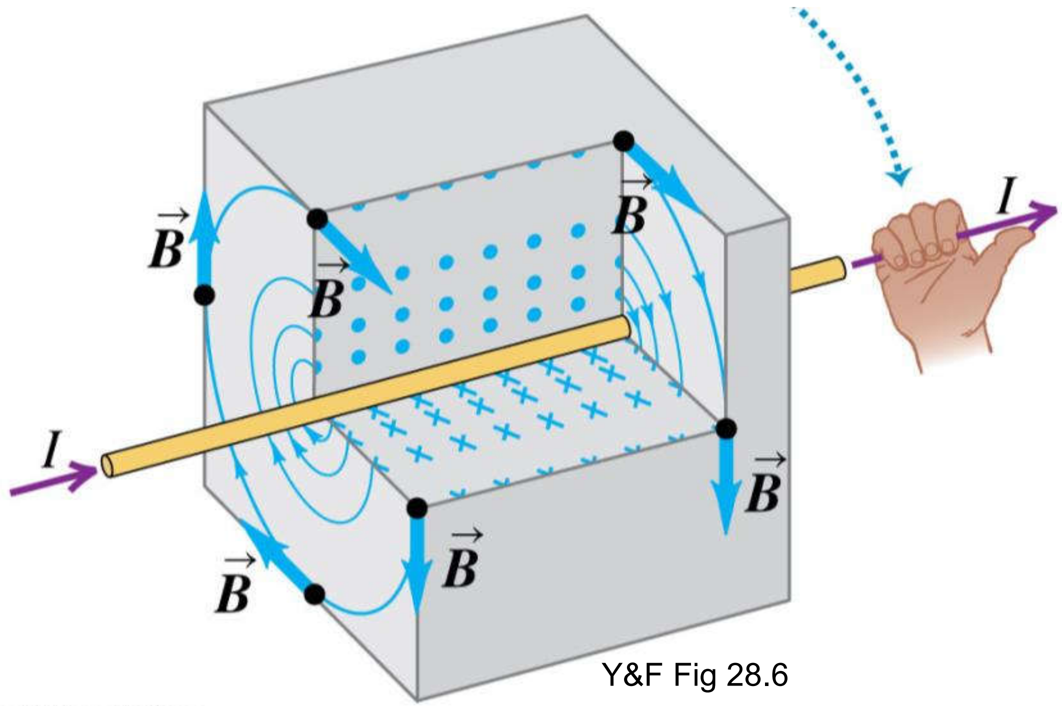
$$\vec{B} = \frac{\mu_0}{4\pi} I \frac{2a}{\rho} \frac{1}{\sqrt{a^2+\rho^2}} \hat{\varphi} \qquad (28.8)$$



Y&F Figure 28.5

Nærme rett leder $(a >> \rho)$:

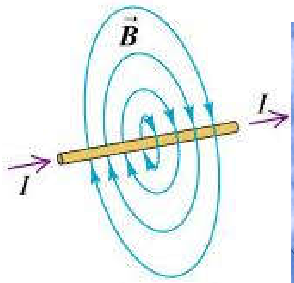
$$B = \frac{\mu_0}{2\pi} \frac{I}{\rho} \qquad (28.9)$$



Y&F Fig 28.6

Felt rundt uendelig lang, rett leder:

$$B = \frac{\mu_0}{2\pi}\frac{I}{\rho}, \qquad \frac{\mu_0}{2\pi} = 2\cdot 10^{-7}\ \text{Tm/A}$$



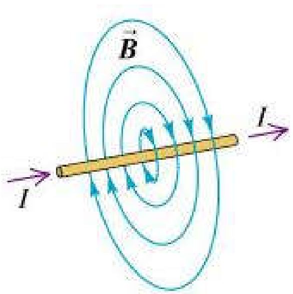
Eksempler:

1) Under én kraftledning:
$I = 1$ kA, $\rho = 100$ m => $B = 2\ \mu$T

2) Nær f. eks. hårføner:
$I = 3$ A, $\rho = 5$ cm => $B = 12\ \mu$T

Jordmagnetismen: $B = 0{,}5$ G $= 50\ \mu$T
(statisk felt)

1) og 2) gjelder for enkeltledere:



For to ledere med motsatt strøm blir *B*-feltet betydelig lavere.

Statens strålevern
Norwegian Radiation Protection Authority

- Gjelder vekselfelt 50 Hz:
- Grenseverdien er 200 µT for befolkningen
- Ved nybygg eller nye anlegg hvor årsgjennomsnittet overskrider 0,4 µT, skal tiltak vurderes.

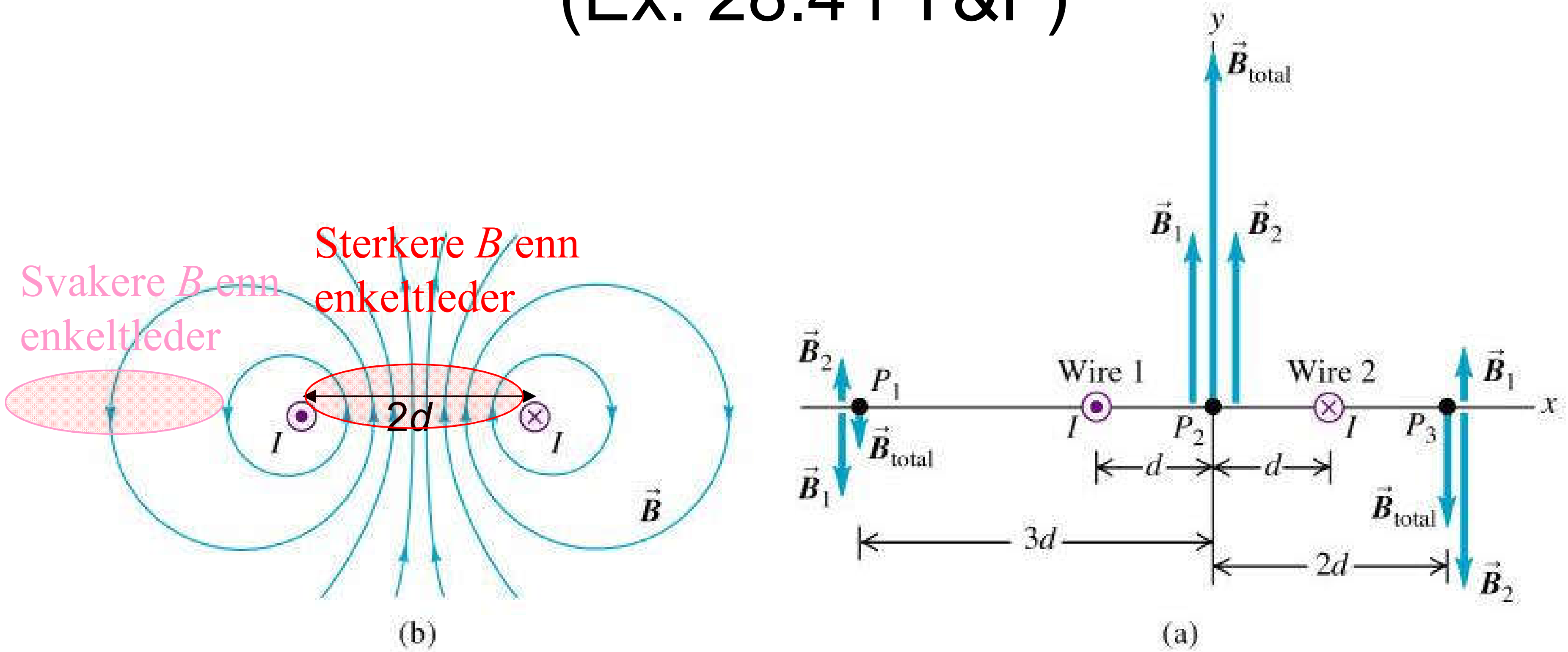
Eksempler på magnetfeltnivå ved høyspentledninger:

Spenningsnivå (kilovolt)	Strømstyrke (Ampere)	Avstand i meter som gir 0,4 µT
22	150	15
22	200	18
66	200	20
66	300	25
132	300	35
132	400	40
300	450	60
300	650	70
420	800	85
420	1100	100

Tabellen viser eksempler på hvor langt fra nærmeste ledning magnetfeltet vil være nede i utredningsnivået 0,4 µT. Eksemplene gjelder vanlig planoppheng, og er satt opp ut fra typiske gjennomsnittsverdier på strømstyrke i ledninger med ulike spenningsnivå.

Fra: http://www.nrpa.no/strom-og-hoyspent

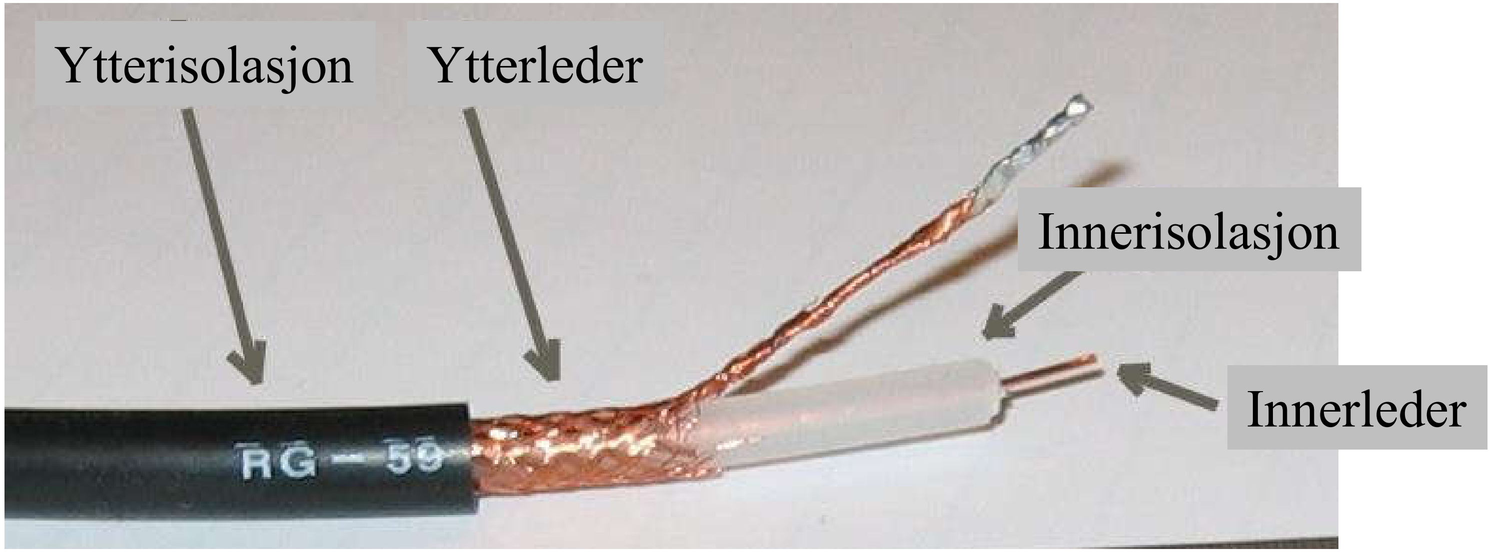
Magnetfelt fra to parallelle ledere
(Ex. 28.4 i Y&F)



For $r >> d$:
B-felt avtar med $1/r^2$,
dvs. betydelig raskere
enn for enkeltleder.

(Fig 28.7)

Utafor koaksialkabel er *B*-feltet null!

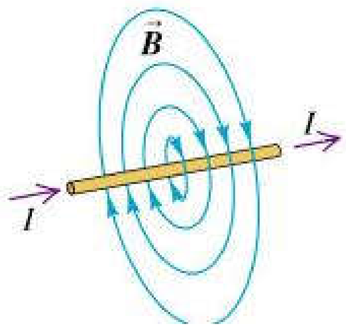


Mer seinere, bl.a. oppgave i regneøving.

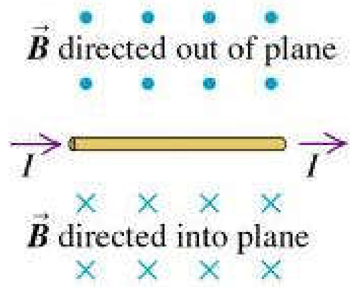
Y&F Fig 28.8

***B*-felt** rundt uendelig lang, rett leder:

$$B = \boxed{\frac{1}{2\pi}\mu_0}\frac{I}{r}$$



Retning: asimutalt (φ-retning)
r = avstand fra lederen

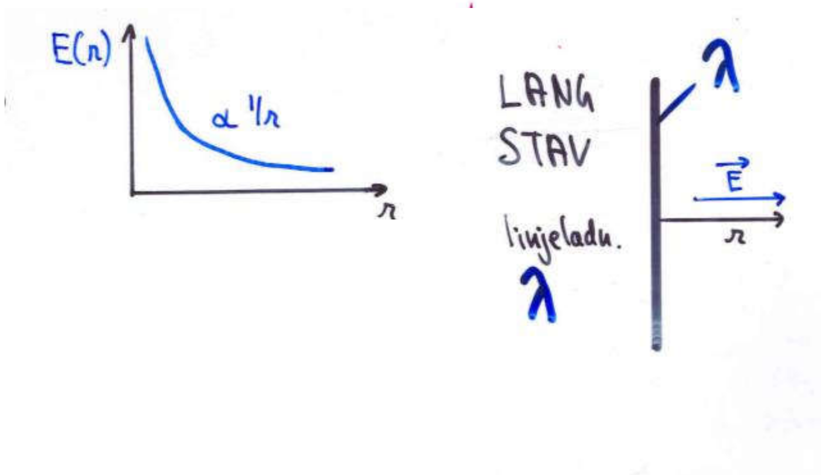


Sammenlikn med:

***E*-felt** rundt uendelig lang, ladd rett leder:

$$E = \boxed{\frac{1}{2\pi}\frac{1}{\varepsilon_0}}\frac{\lambda}{r}$$

Retning: radielt (*r*-retning)
r = avstand fra lederen



Kap 28: Magnetiske kilder

- **Elektrostatikk:**

$$\vec{E} = \frac{1}{4\pi\varepsilon_0}\frac{q\hat{r}}{r^2}$$ (Coulombs lov)

- **Magnetostatikk:**

Enkeltladning:

$$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$$ (28.2)

Strøm i leder:

$$\vec{B} = \int_{\text{ledn.}} \mathrm{d}\vec{B} = \frac{\mu_0 I}{4\pi}\int_{\text{ledn.}} \frac{\mathrm{d}\vec{s}\times\hat{r}}{r^2}$$ (28.7) (Biot-Savart)

1819-25:	Vitenskapelig arbeid: Hans Christian Ørsted, André Ampere, Jean-Baptist Biot, Felix Savart, Michael Faraday, Joseph Henry

- **Eks. 1: Rett leder**
- **28.4: Definisjon 1 ampere**
- **Eks. 2: Sirkulær sløyfe**

- **Amperes lov**

28.4 Kraft mellom to parallelle ledere

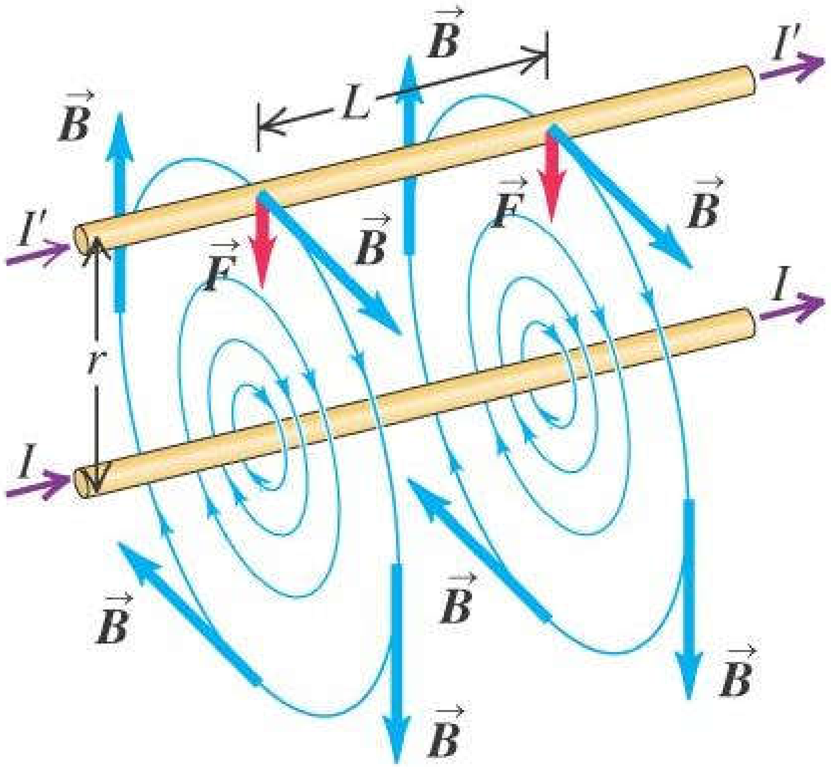


Figure 28.9

$$F' = I_1 I_2 \mu_0/(2\pi r)$$

Definisjon 1 A:

$2 \cdot 10^{-7}$ N/m = 1 A 1 A $\mu_0/(2\pi$ 1 m)

.. er i praksis definisjon av $\mu_{0:}$

$\mu_0 = 2\pi \cdot 2 \cdot 10^{-7}$ N/A^2 $= 4\pi \cdot 10^{-7}$ Tm/A

Definisjon av 1 ampere (grunnenhet i SI-systemet)

- En ampere er den konstante elektriske strømmen som frambringer en gjensidig lineær kraft på $2 \cdot 10^{-7}$ newton per meter leder når strømmen går gjennom hver av to rettlinjete, parallelle, uendelige lange ledere med sirkulært og neglisjerbart lite tverrsnitt, og lederne er anbrakt i én meters innbyrdes avstand i tomt rom.

- ampere er en av sju SI-grunnenheter:

meter	-	lengde
kilogram	-	masse
sekund	-	tid
ampere	-	strømstyrke
kelvin	-	temperatur
mol	-	stoffmengde
candela	-	lysstyrke

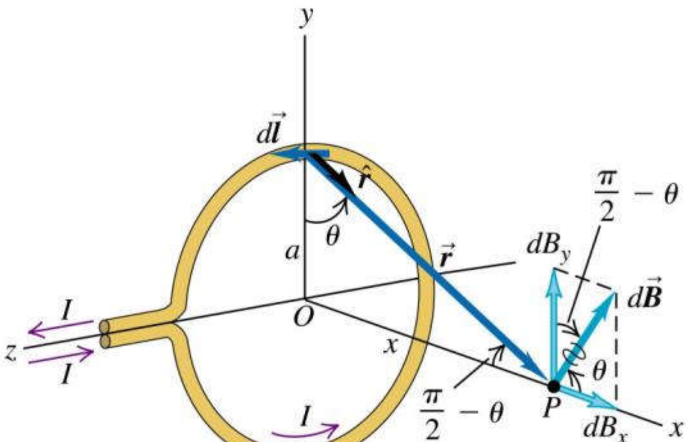
Alle andre enheter er avledet fra disse, for eksempel

$$N = kg\ m\ s^{-2}$$

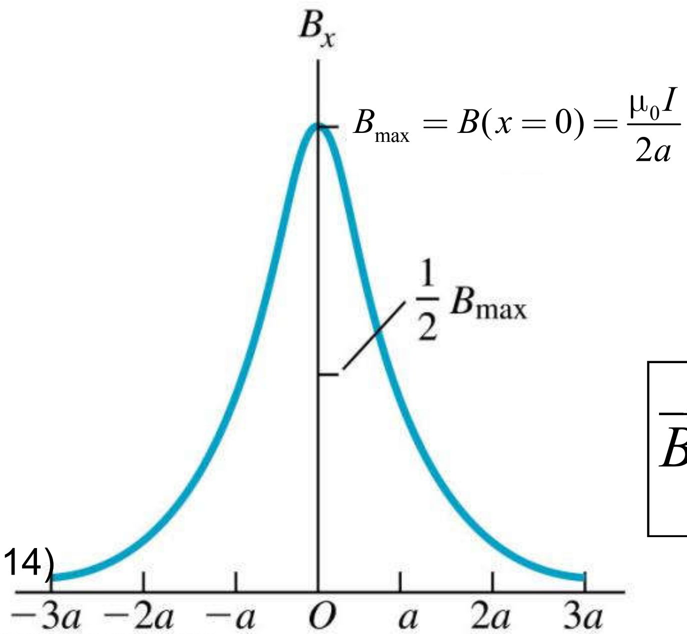
$$V = J/C = kg\ m^2\ s^{-3}\ A^{-1}$$

(se formelarket)

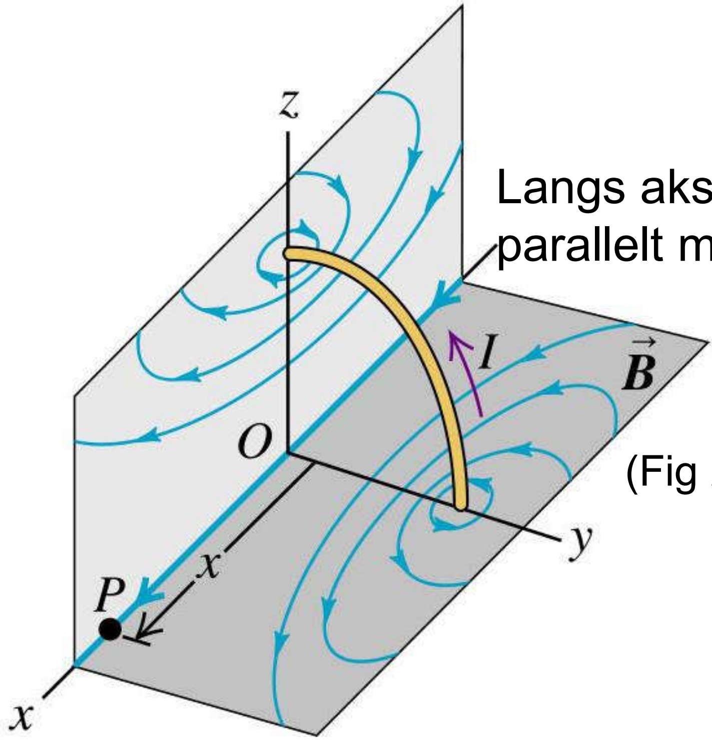
Eks. 2: *B*-feltet på aksen i en sirkulær strømsløyfe: (kap 28.5)



(Fig 28.12)



(Fig 28.14)



Langs aksen går feltet parallelt med aksen

(Fig 28.15)

$$\vec{B}(x) = \frac{\mu_0 I a^2}{2(x^2 + a^2)^{3/2}} \hat{i} \qquad (28.15)$$

Kap. 28:

Eks. 1: *B*-feltet på midtnormal til rett leder, lengde 2*a*

$$\vec{B} = \frac{\mu_0}{4\pi} I \frac{2a}{\rho} \frac{1}{\sqrt{a^2+\rho^2}} \hat{\varphi} \qquad \vec{B}(\rho \ll a) = \frac{\mu_0}{2\pi} \frac{I}{\rho} \hat{\varphi}$$

Eks. 2: *B*-feltet på aksen i en sirkulær strømsløyfe, radius *a*

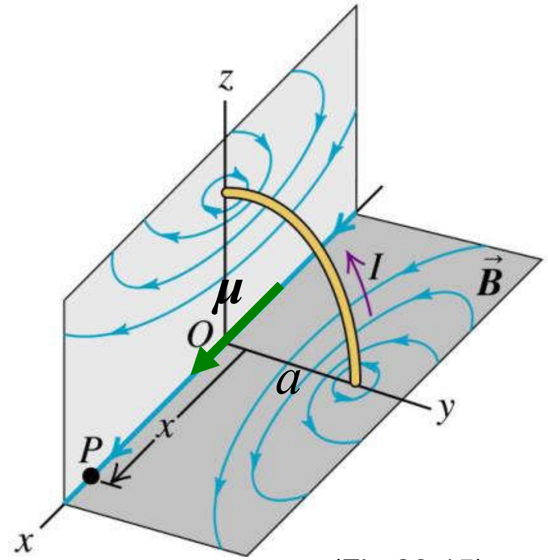
$$\boxed{\vec{B}(x) = \frac{\mu_0 I a^2}{2(x^2+a^2)^{3/2}} \hat{i}} \qquad \boxed{\vec{B}(x=0) = \frac{\mu_0 I}{2a} \hat{i}} \qquad \boxed{\vec{B}(x \gg a) = \frac{\mu_0 I a^2}{2x^3} \hat{i}}$$

Eks. 3: *B*-feltet i sentrum av kvadratisk strømsløyfe
(Øving 10, opg. 4: *B*-feltet på hele midtnormalen)

$$\begin{aligned} \vec{B}(x=0) &= \frac{\mu_0 I}{2a} \frac{4}{\sqrt{2}\pi} \hat{i} \\ &= \vec{B}_{\text{sirkulær}}(x=0) \cdot \frac{4}{\sqrt{2}\pi} \\ &= \vec{B}_{\text{sirkulær}}(x=0) \cdot 0{,}900 \end{aligned}$$

Eks. 2: Feltet på aksen i en sirkulær strømsløyfe

$$\vec{B}(x) = \frac{\mu_0 I a^2}{2(x^2 + a^2)^{3/2}} \hat{i} \qquad (28.15)$$

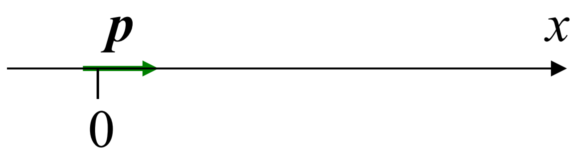


(Fig 28.15)

Langt unna $x >> a$: $\vec{B}(x) = \frac{\mu_0 I a^2}{2x^3} \hat{i} = \frac{\mu_0}{2\pi} \frac{\vec{\mu}}{x^3}$

sløyfas dipolmoment $\boldsymbol{\mu} = I\pi a^2$

Analogi:
Langt unna elektrisk dipol:
(Øv. 6, opg. 2d) $\vec{E}(x) = \frac{1}{2\pi\varepsilon_0} \frac{\vec{p}}{x^3}$



Kap 28: Magnetiske kilder

- **Elektrostatikk:**

  Coulombs lov

  → hjelpelov: Gauss' lov (når symmetri)

- **Magnetostatikk:**

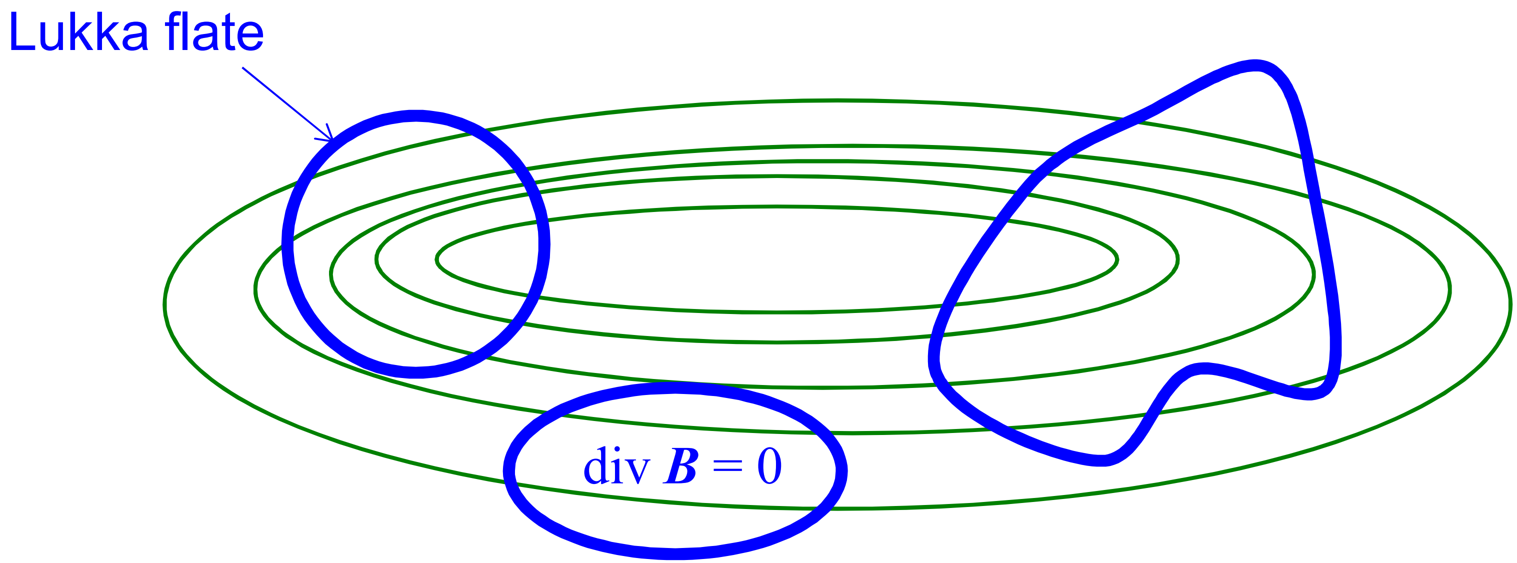
  Biot-Savarts lov

  → hjelpelov: Amperes lov (når symmetri)

Gauss' lov for *B*-felt:

Feltlinjer er lukka kurver

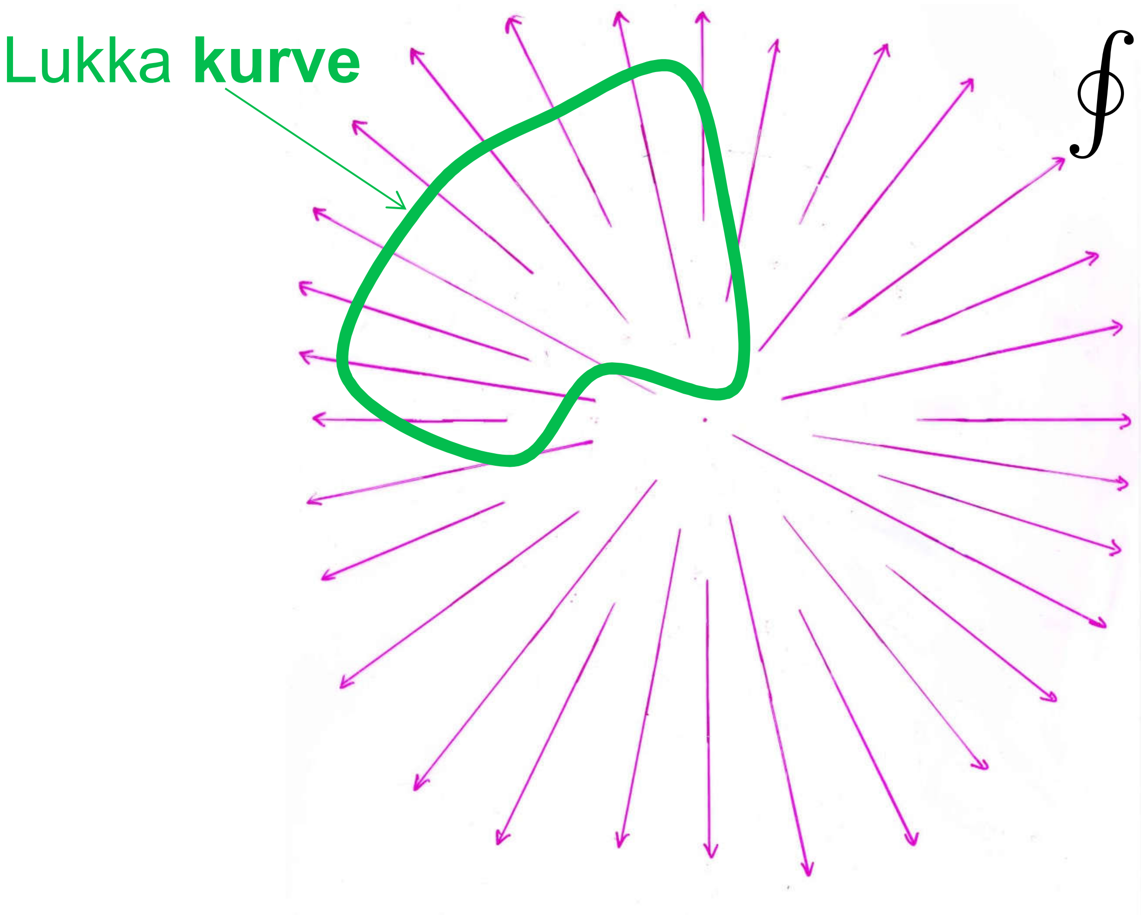
=> Nettofluks = 0 ut fra lukka flate



Kap. 23: Sirkulasjonsloven for *E*-felt

(konservativt felt):

Integrasjon over lukka **kurve** = 0

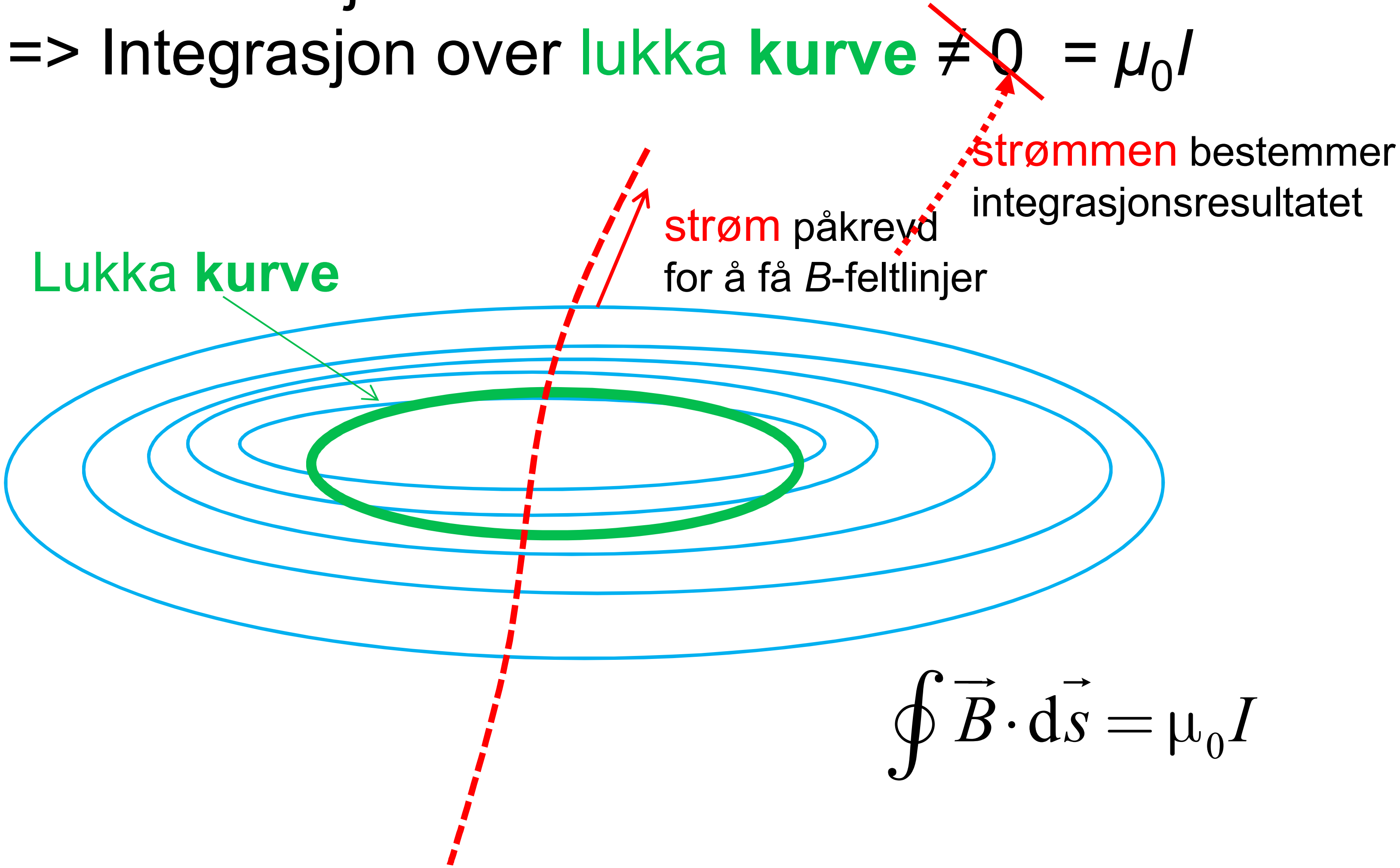


$$\oint \vec{E} \cdot \mathrm{d}\vec{s} = 0$$

Sirkulasjonsloven for *B*-felt:

Feltlinjer er lukka kurver

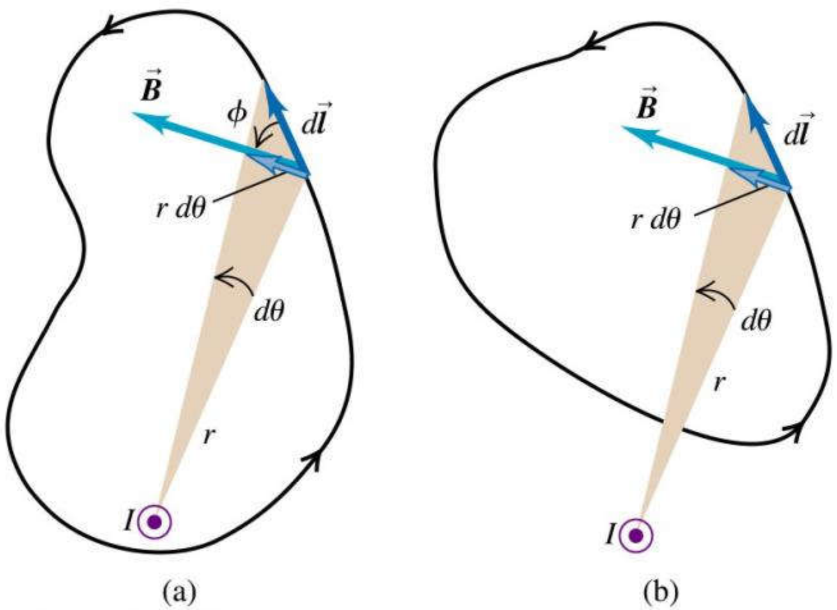
=> Integrasjon over lukka **kurve** ~~≠ 0~~ $= \mu_0 I$



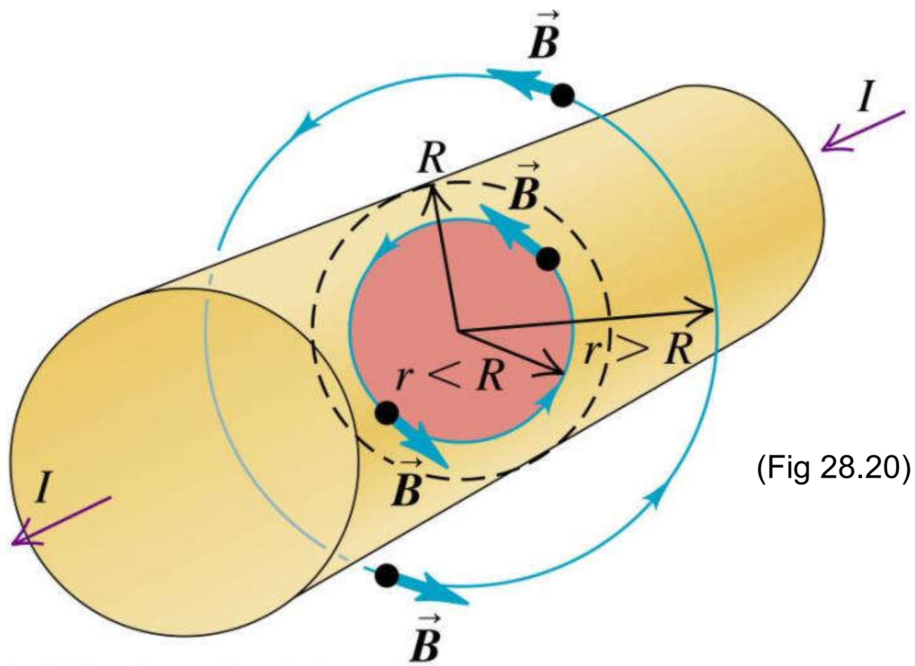
$$\oint \vec{B} \cdot \mathrm{d}\vec{s} = \mu_0 I$$

Amperes lov

$\int \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{s} = \mu_0\, I$ over lukka kurve, der I er totalstrøm innenfor kurva



(Fig 28.17)

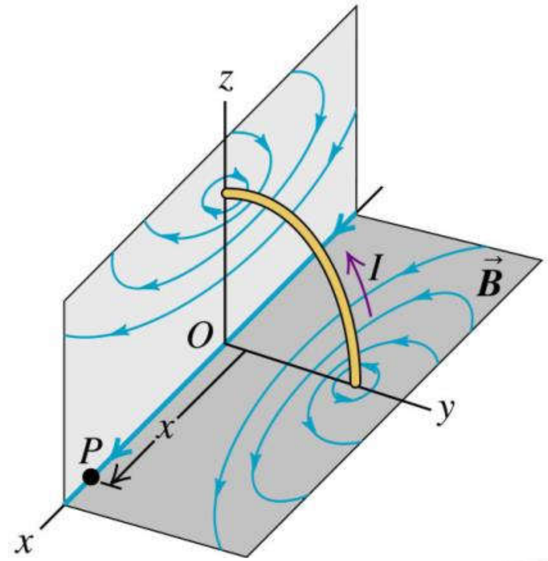


(Fig 28.20)

Gjelder alle integrasjonsveger,

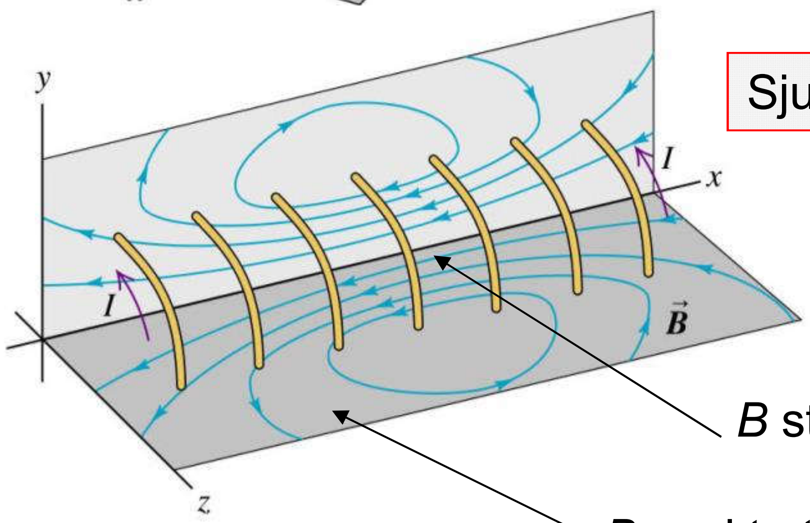
men er nyttig kun i (sylinder)symmetriske konfigurasjoner. F. eks. rundt leder: $B = \mu_0\, I/2\pi r$

Eks. 4. Solenoide (Ex. 28.10)



Én sløyfe

(Fig 28.15)



Sju sløyfer

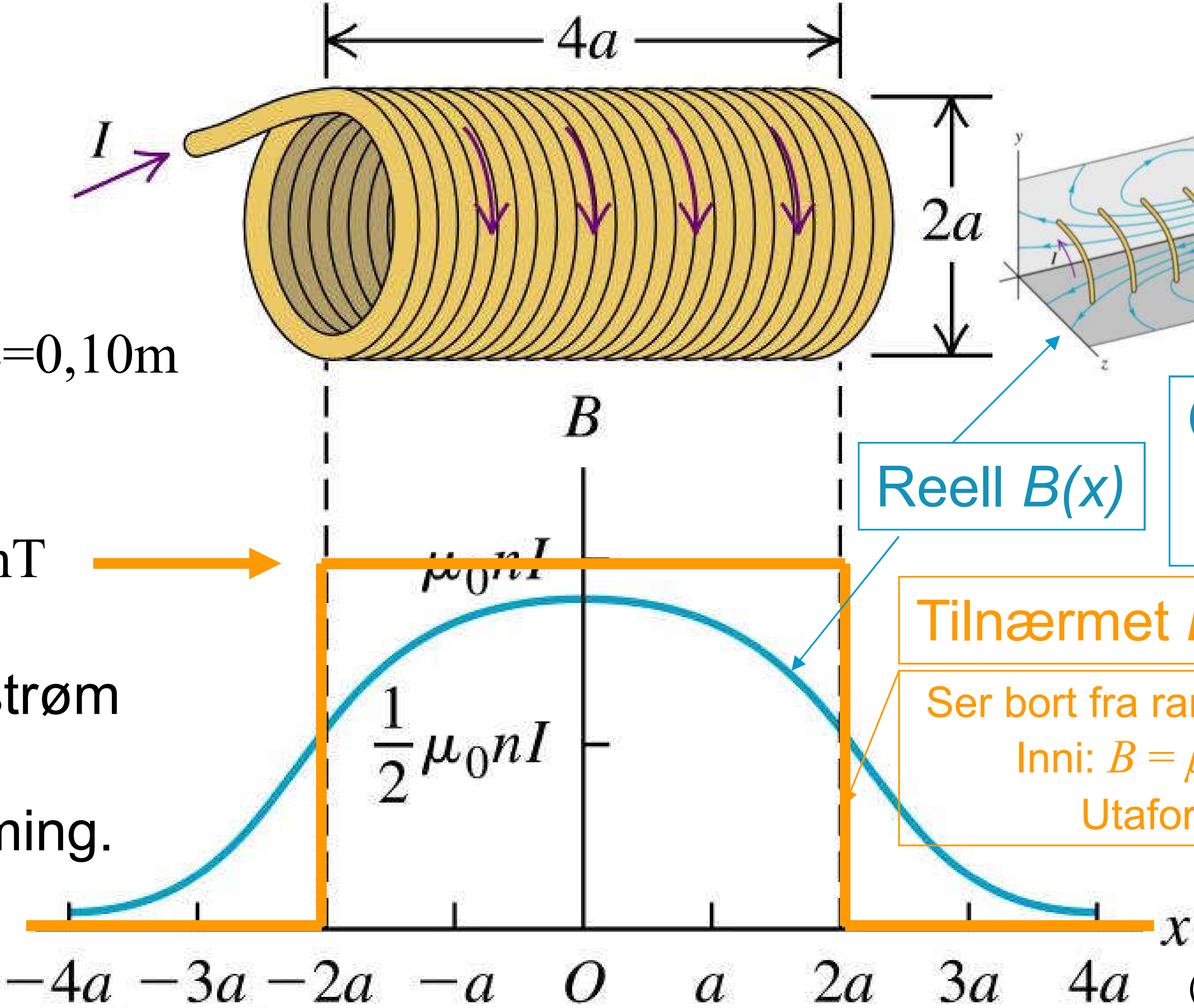
(Fig 28.22)

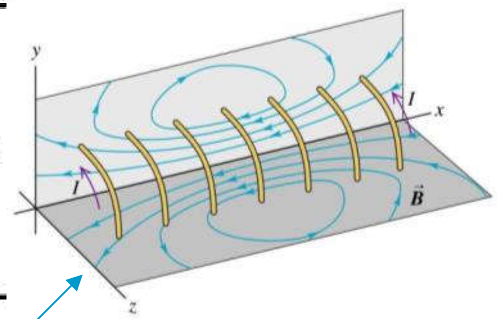
B sterkt inni

B svakt utafor

Mange sløyfer: Antar *B* konst. inni,
B = 0 utafor

Eks. 4: Solenoide (mange sirkulære strømsløyfer)





(Fig 28.24)

Eks:
N=400 L=0,10m
I=5,0A
=>
B = 25 mT

Større strøm gir oppvarming.

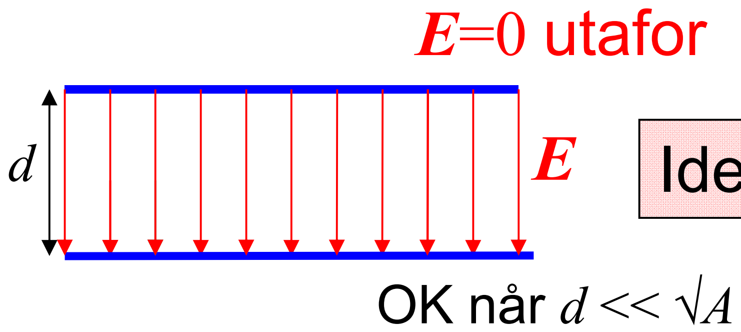
Reell $B(x)$

(beregnet i tekst til Lab 2

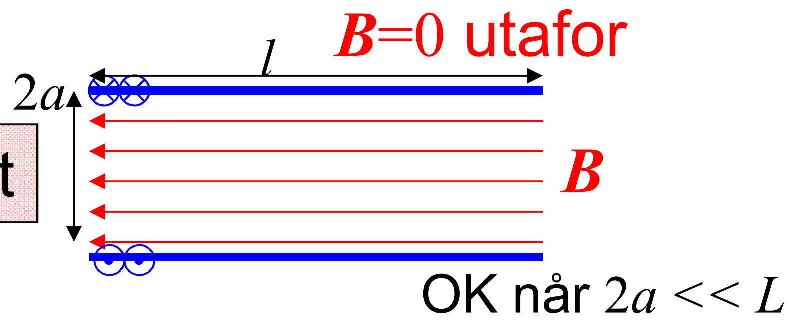
Tilnærmet $B(x)$

Ser bort fra randeffekter:
Inni: $B = \mu_0 I\, N/l$
Utafor: $B=0$

E i parallellplatekondensator

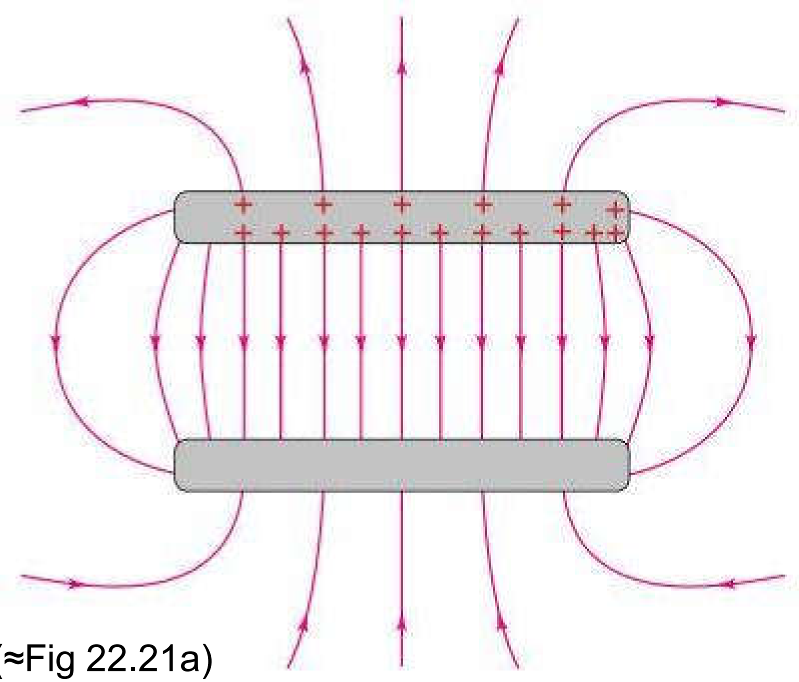


B i solenoide

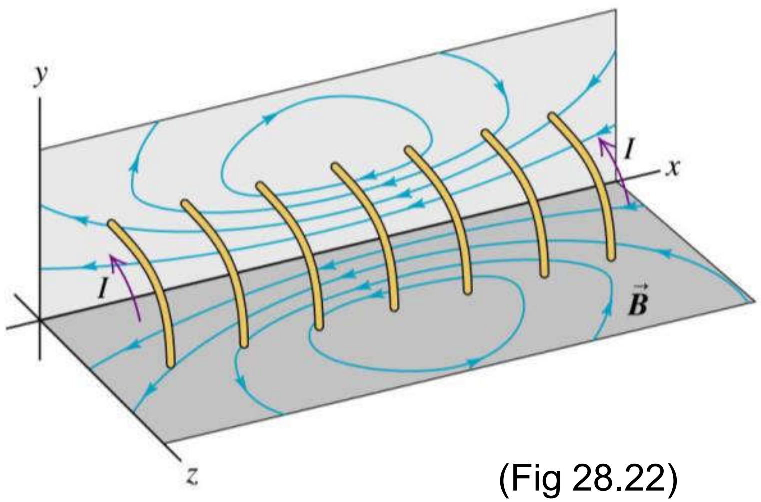


Idealisert

Reelt



(≈Fig 22.21a)



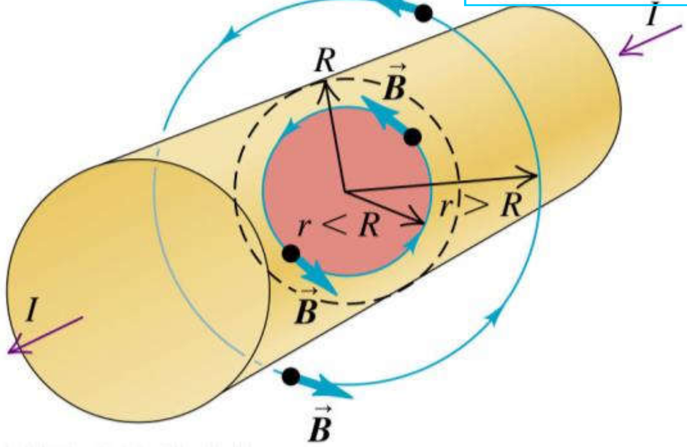
(Fig 28.22)

|*B*| inni og utafor en sylinderleder med uniform strøm *I*

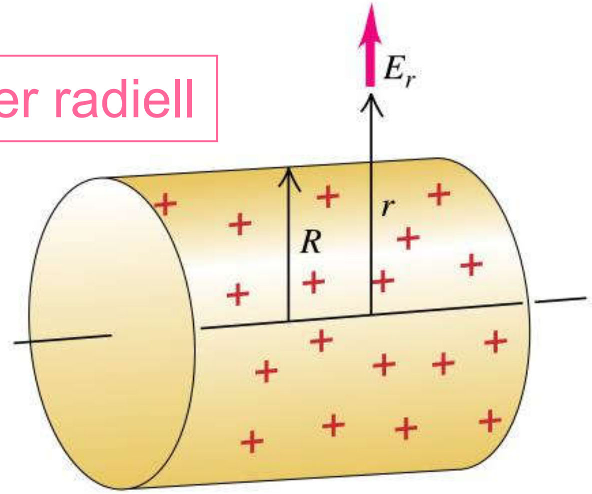
analog til

|*E*| inni og utafor en sylinder med uniform ladning λ

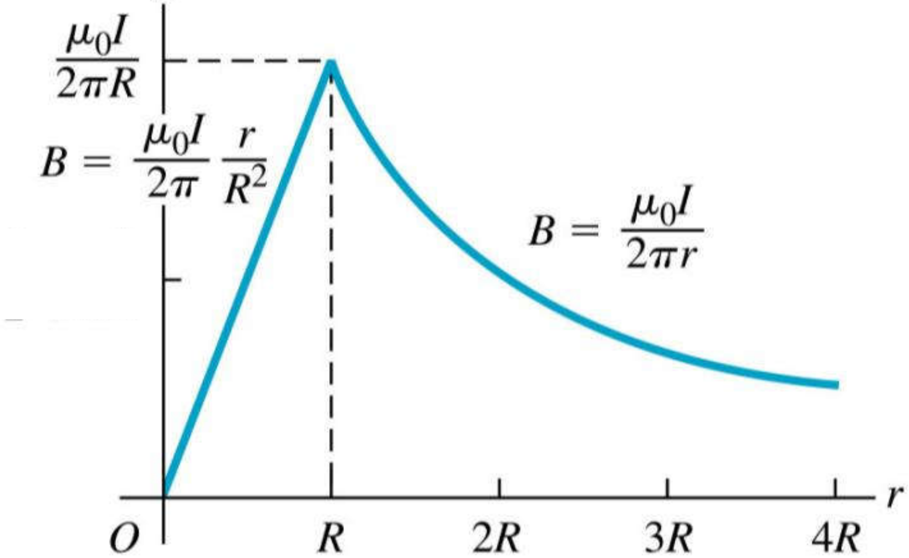
B er asimutal



E er radiell

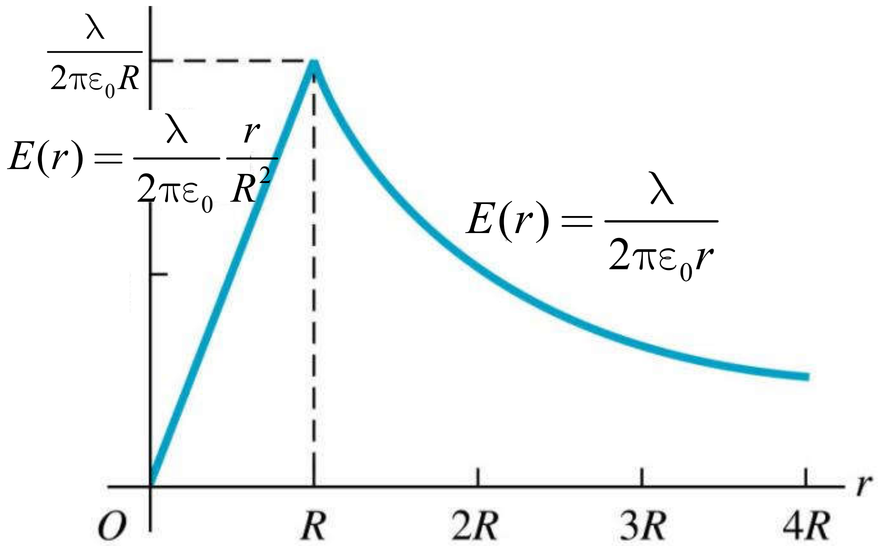


(Ex. 28.8)



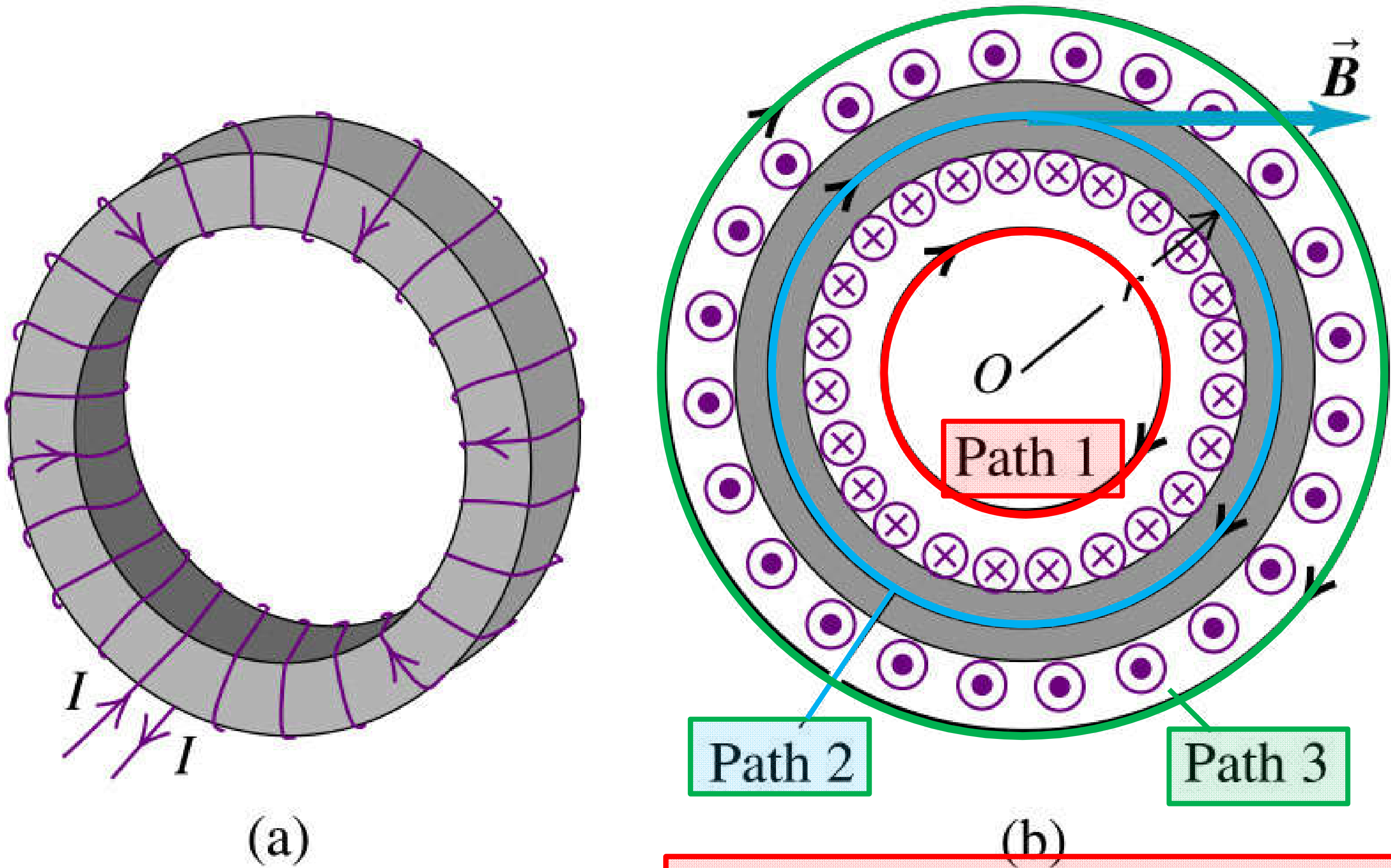
E

(≈Ex. 23.10)



Feltet i toroid solenoide: (Ex. 28.10)

Mer
Amperes lov
i Øv. 11 og 12



(Fig 28.25)

Path 1: $I_{incl} = 0 \quad => B = 0$

Path 2: $I_{incl} = NI \quad => B \approx \mu_0 NI/2\pi r$

Path 3: $I_{incl} = NI + N(-I) = 0 \quad => B = 0$

Øving 9, flervalg:

a) En punktladning q er plassert i det ene hjørnet av en kube. Hva blir elektrisk fluks gjennom den skraverte (høyre) sideflata i figuren?

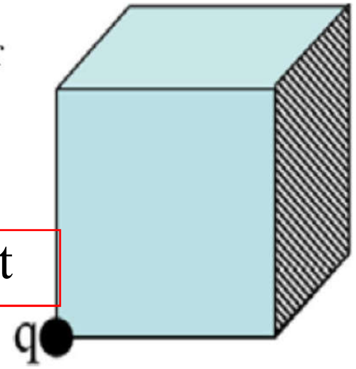
A) q

B) $q/3$

C) $q/4$

D) $q/8$

E) $q/24$



Elek. fluks = fluks til D-feltet

$$\Phi = D\,A$$

Young & Freedman, kap. 22.2:

bruker
Elek. fluks
= fluks til E-feltet

$$\Phi_E = E\,A$$

If the area A is flat but not perpendicular to the field $\vec{E}$, then fewer field lines pass through it. In this case the area that counts is the silhouette area that we see when looking in the direction of $\vec{E}$. This is the area $A_\perp$ in Fig. 22.6b and is equal to $A\cos\phi$ (compare to Fig. 22.5b). We generalize our definition of electric flux for a uniform electric field to

$$\Phi_E = EA\cos\phi \qquad \text{(electric flux for uniform } \vec{E}\text{, flat surface)} \qquad (22.1)$$

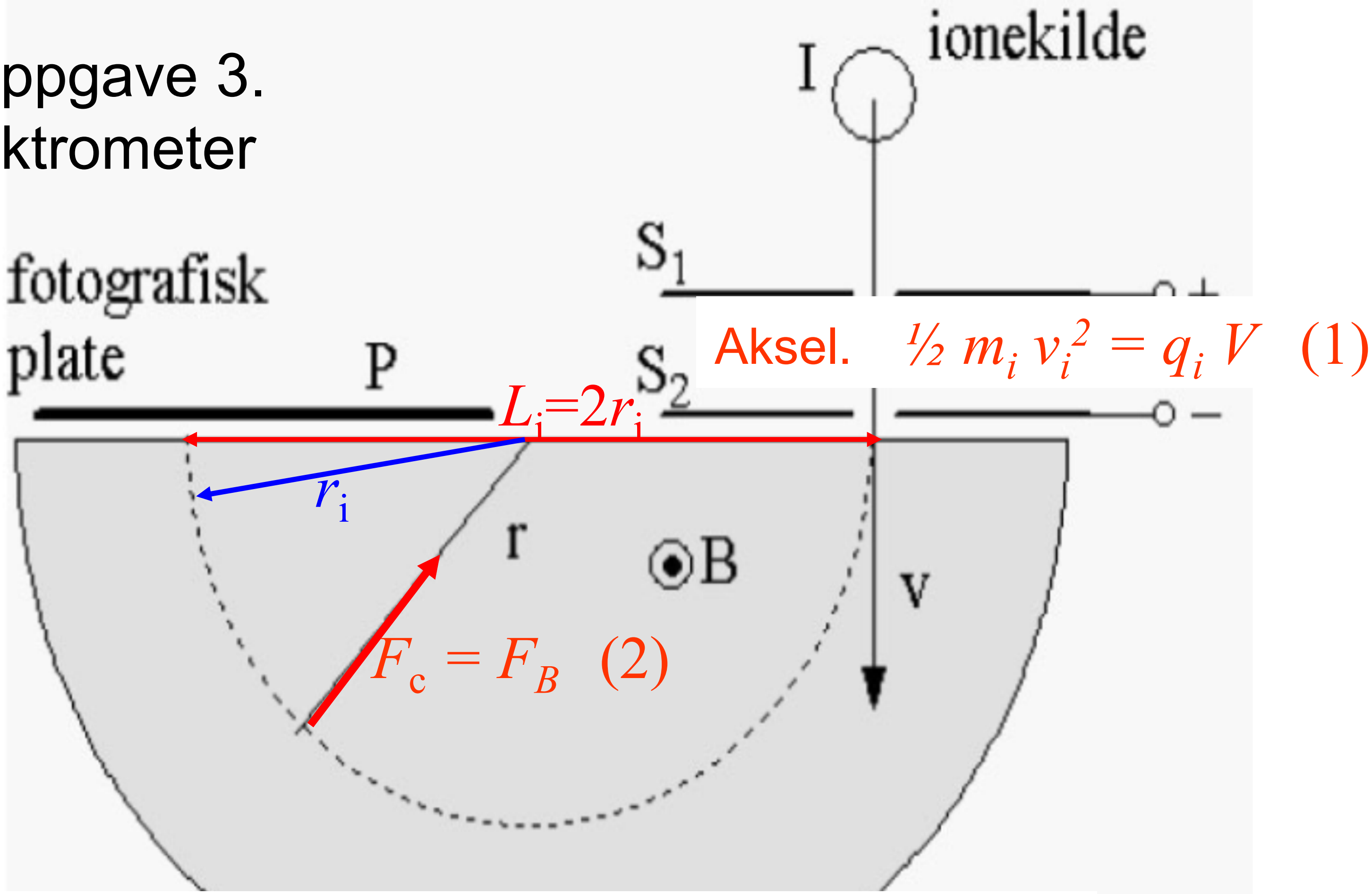
Since $E\cos\phi$ is the component of $\vec{E}$ perpendicular to the area, we can rewrite Eq. (22.1) as

$$\Phi_E = E_\perp A \qquad \text{(electric flux for uniform } \vec{E}\text{, flat surface)} \qquad (22.2)$$

In terms of the vector area $\vec{A}$ perpendicular to the area, we can write the electric flux as the scalar product of $\vec{E}$ and $\vec{A}$:

$$\Phi_E = \vec{E}\cdot\vec{A} \qquad \text{(electric flux for uniform } \vec{E}\text{, flat surface)} \qquad (22.3)$$

Øving 9, oppgave 3.
Massespektrometer



a) Likn. (1) for protonet

b) Likn (2) for protonet $m_i v_i^2 / r_i = q_i v_i B$ (2)

c) Søk etter masseforholdet m_1/m_p
med likn (1) og (2) for i=1 (masse 1) og i=p (protonet).
Tilsvarende for m_2/m_p.

Amperes lov, rekap.

$$\int \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{s} = \mu_0 I \quad \text{(Amp)}$$

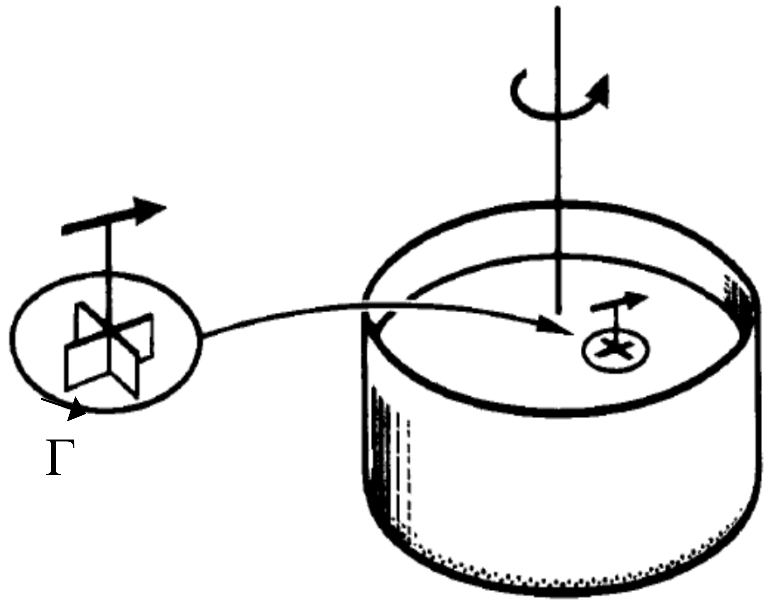
over lukka kurve, der I er totalstrøm innenfor kurva

$$\boxed{\text{curl}\, \boldsymbol{B} = \mu_0 \boldsymbol{J} \quad \text{(Amp-diff)}}$$

Maxwells likninger (så langt, statikk)

Integralform		Differensialform
$\oiint \vec{E} \cdot \mathrm{d}\vec{A} = Q / \varepsilon$	Gauss' lov ***E***	$\vec{\nabla} \cdot \vec{E} = \rho / \varepsilon$
$\oiint \vec{B} \cdot \mathrm{d}\vec{A} = 0$	Gauss' lov ***B***	$\vec{\nabla} \cdot \vec{B} = 0$
$\oint \vec{B} \cdot \mathrm{d}\vec{s} = \mu_0 I$	Amperes lov	$\mathrm{curl}\vec{B} = \vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$
$\oint \vec{E} \cdot \mathrm{d}\vec{s} = 0$		$\mathrm{curl}\vec{E} = \vec{\nabla} \times \vec{E} = \vec{0}$

curl
-- kan i vannstrøm demonstreres med et (infinitesimalt) skovlhjul:



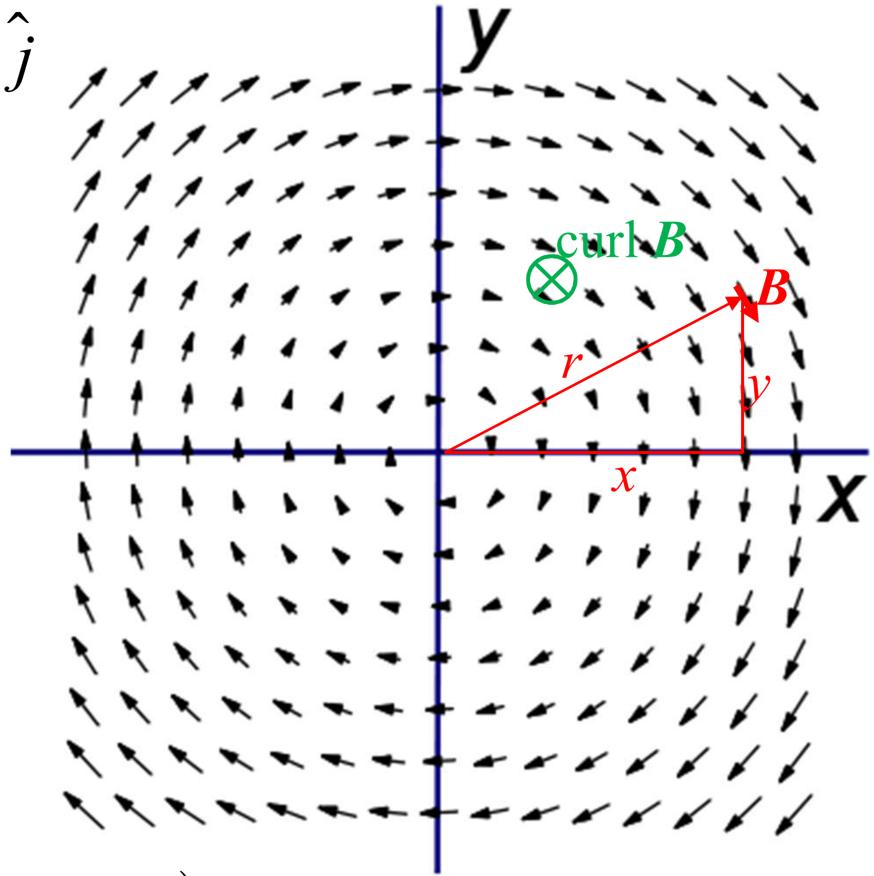
Curl

Eks. forrige time:

$$\vec{B}(x,y,z) = [y, -x, 0] = y\hat{i} - x\hat{j}$$

$$\vec{B}(r,\varphi,z) = -r\hat{\varphi}$$

(konstanter utelatt, feil enheter for B)



Inni sylindrisk leder:

$$\vec{B}(r,\varphi,z) = -\frac{\mu_0}{2} J\, r\, \hat{\varphi}$$

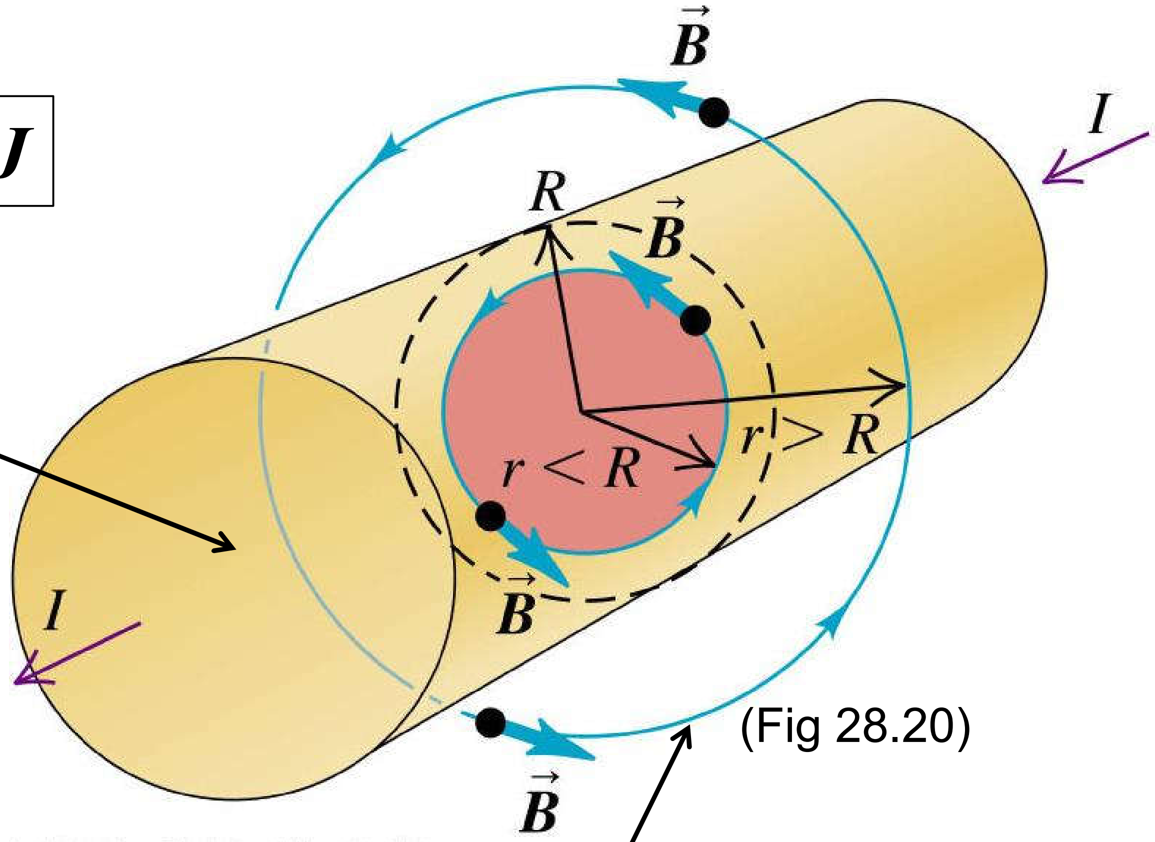
$$\text{curl } \vec{B} = \mu_0 J\, \hat{k} = \mu_0 \vec{J}$$

$$\text{curl}\vec{B} = \begin{vmatrix} \hat{i} & \hat{j} & \hat{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ y & -x & 0 \end{vmatrix} = 0\cdot\hat{i} + 0\cdot\hat{j} + \left(\frac{\partial(-x)}{\partial x} - \frac{\partial y}{\partial y}\right)\hat{k} = -2\hat{k}$$

Eks. 5: Feltet inni og utafor en ledning

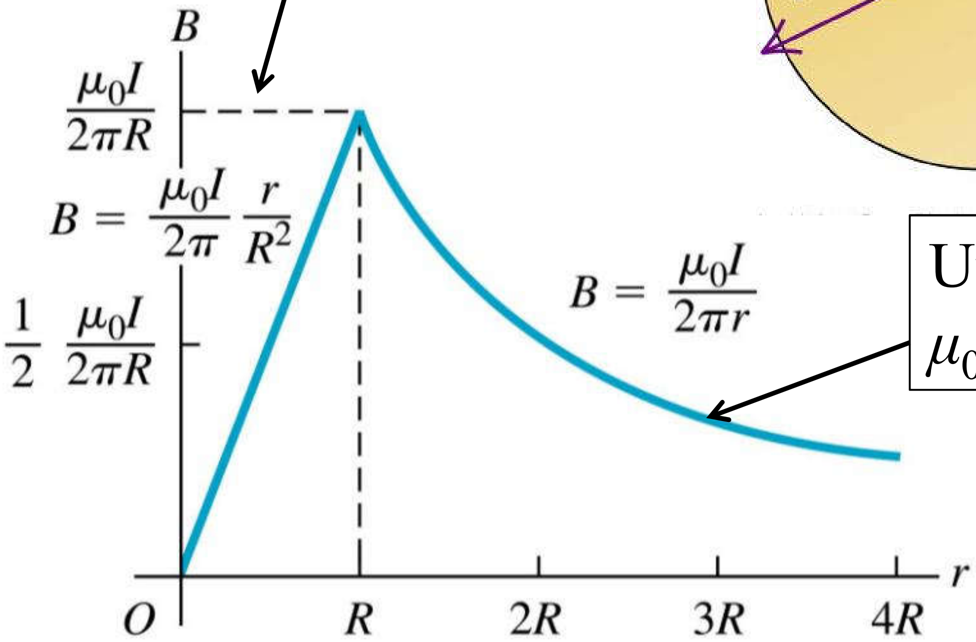
Ampere: curl $\boldsymbol{B} = \mu_0 \boldsymbol{J}$

Inni:
$\mu_0 \boldsymbol{J} = \text{curl } \boldsymbol{B}$



(Fig 28.20)

Utafor:
$\mu_0 \boldsymbol{J} = \boldsymbol{0} = \text{curl } \boldsymbol{B}$



(Fig 28.21)

Maxwells likninger i Notat 4

Statikk

$E = D/\varepsilon$

$H = B/\mu$ defineres straks

Integralform		Differensialform
$\oint \vec{D} \cdot \mathrm{d}\vec{A} = Q$	Gauss' lov ***D***	$\vec{\nabla} \cdot \vec{D} = \rho$
$\oint \vec{B} \cdot \mathrm{d}\vec{A} = 0$	Gauss' lov ***B***	$\vec{\nabla} \cdot \vec{B} = 0$
$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = I + \frac{\partial \Phi}{\partial t}$	Amperes lov	$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$
$\oint \vec{E} \cdot \mathrm{d}\vec{\ell} = 0 \quad \left(- \frac{\partial \Phi_B}{\partial t}\right)$	Faradays lov	$\vec{\nabla} \times \vec{E} = 0 \quad \left(- \frac{\partial \vec{B}}{\partial t}\right)$

Kap 28: Magnetiske kilder

- **Elektrostatikk:**

  Ladning *q* påvirkes av kraft *q**E*** (Coulombs lov)

  → Definisjon *E*-felt

  E-feltet skapes fra ladninger (Coulombs lov)

- **Magnetostatikk:**

  Ladning *q* **i bevegelse** påvirkes av kraft *q**v*** x ***B***

  → Definisjon *B*-felt (Lorentzkrafta)

  B-feltet skapes fra ladninger **i bevegelse**

  (Biot-Savarts lov)

- **Hjelpelover:**

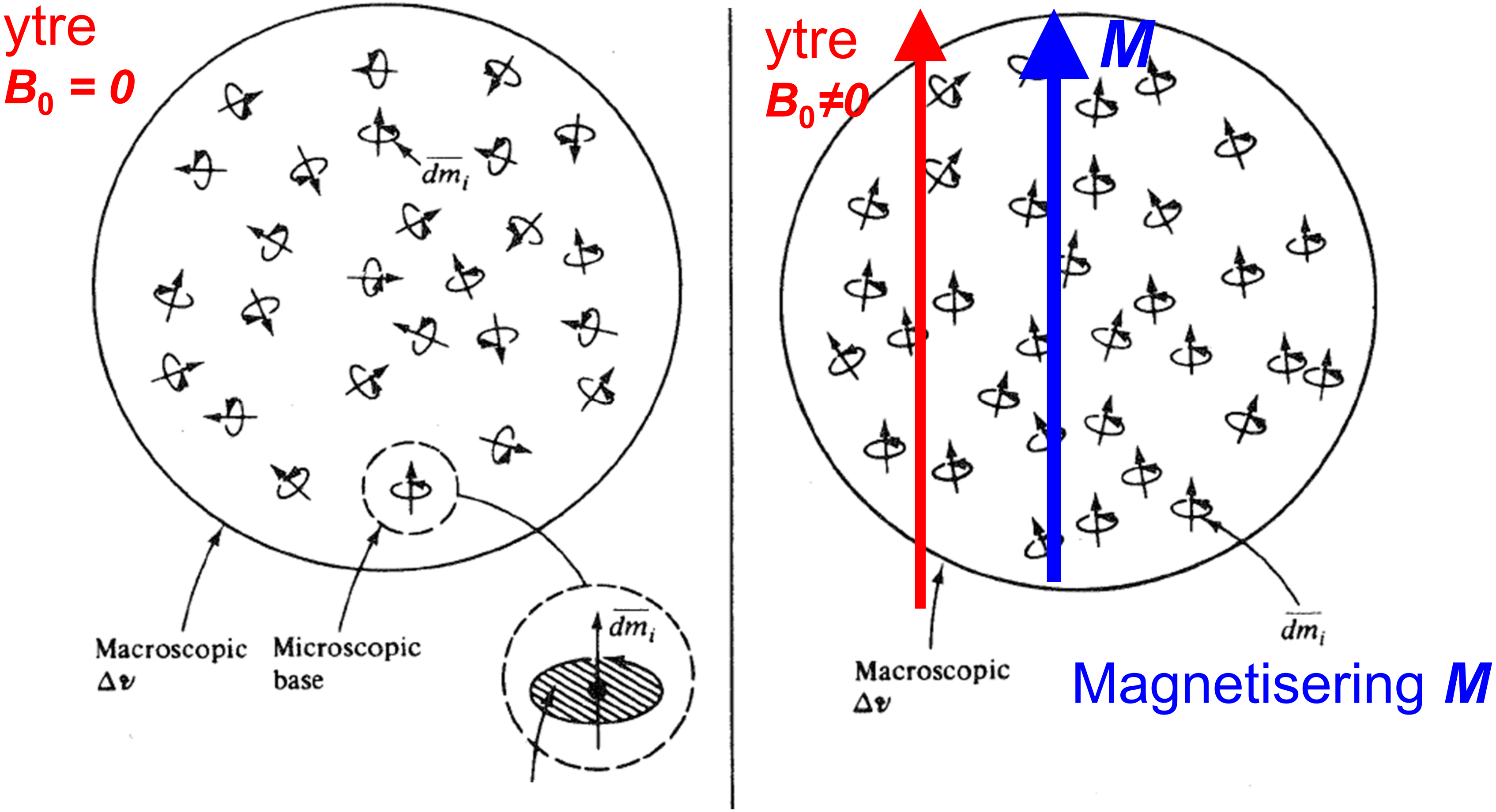
  Elektrostatikk: Gauss' lov

  Magnetostatikk: Amperes lov

- **Til slutt: Magnetiske materialer**

  Ferromagnetisk materiale. Magnetisering. ***M***-vektor og ***H***-vektor

Atomære magnetiske moment $\boldsymbol{\mu}$ (= $\overline{dm_i}$) i ytre magnetisk felt $\boldsymbol{B}$

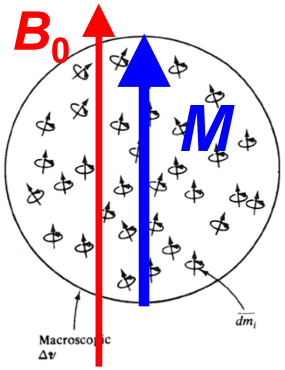


Paramagnetiske og ferromagnetiske:
Innretting av magn.moment $\boldsymbol{\mu}$

Tre typer magnetisk materiale:

Type	Effekt	Årsak: Ytre $\boldsymbol{H}_0$ …..
Dia-magnetisk	***B***-felt ↓	induserer magn.mom. $\boldsymbol{\mu}$ med $\boldsymbol{\mu} \parallel (-\boldsymbol{H})$
Para-magnetisk	***B***-felt ↑	innretter permanente $\boldsymbol{\mu}$ med $\boldsymbol{\mu} \parallel \boldsymbol{H}$
Ferro-magnetisk	***B***-felt ↑↑↑↑↑↑↑↑↑	innretter permanente $\boldsymbol{\mu}$ med $\boldsymbol{\mu} \parallel \boldsymbol{H}$ **Mange**

Hva vi har lært:



- Magnetisering, definisjon: $\boldsymbol{M} = \sum \boldsymbol{\mu} \,/\, \text{volum}$

  [analogi: $\boldsymbol{P} = \sum \boldsymbol{p} \,/\, \text{volum}$]

- Magnetisk feltstyrke: $\boldsymbol{H} = \boldsymbol{B}/\mu_0$ (i tomrom)

  [$\boldsymbol{E} = \boldsymbol{D}/\varepsilon_0$]

- Magnetisering, eksperimentelt: $\boldsymbol{M} = \chi_m \boldsymbol{H}$ [$\boldsymbol{P} = \chi_e \varepsilon_0 \boldsymbol{E}$]

- Totalt ***B***-felt i magnetisk materiale:

  $\boldsymbol{B} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{M} = \mu_0 \mu_r \boldsymbol{H}$ [$\boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} = \varepsilon_r \varepsilon_0 \boldsymbol{E}$]

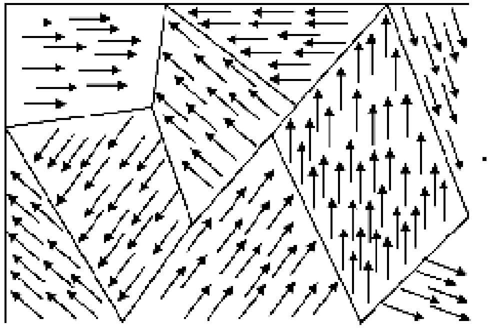
m.m.

$$\boldsymbol{B} = \mu_0 \mu_r \boldsymbol{H}$$

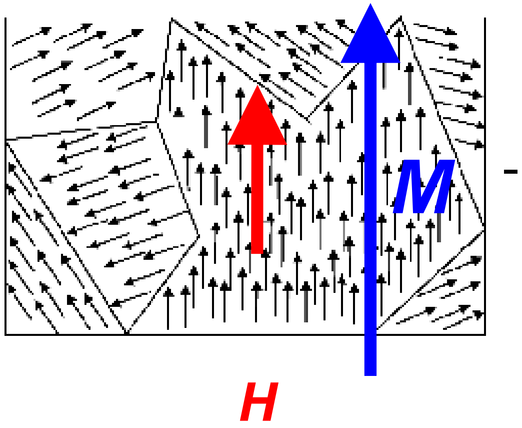
TABLE 9-1 REPRESENTATIVE VALUES FOR PERMEABILITY μ_r FOR SEVERAL MATERIALS

Material	Type	μ_r
Bismuth	Diamagnetic	0.9999834
Silver	Diamagnetic	0.99998
Copper	Diamagnetic	0.999991
Vacuum	Nonmagnetic	1.00
Aluminum	Paramagnetic	1.00002
Nickel chloride	Paramagnetic	1.00004
Cobalt	Ferromagnetic	250
Nickel	Ferromagnetic	600
Mild steel	Ferromagnetic	2,000
Iron	Ferromagnetic	5,000
Mumetal	Ferromagnetic	100,000
Supermalloy	Ferromagnetic	800,000

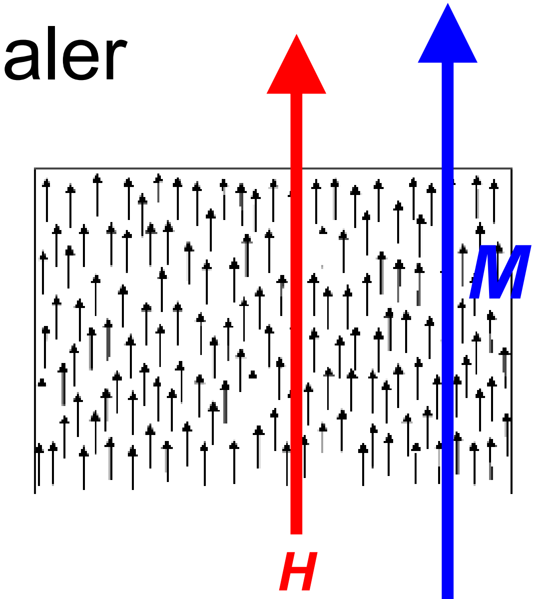
Ferromagnetiske materialer



Ytre *H* = 0:
Magn.moment ***μ*** samordnet innenfor domener (~100 μm)



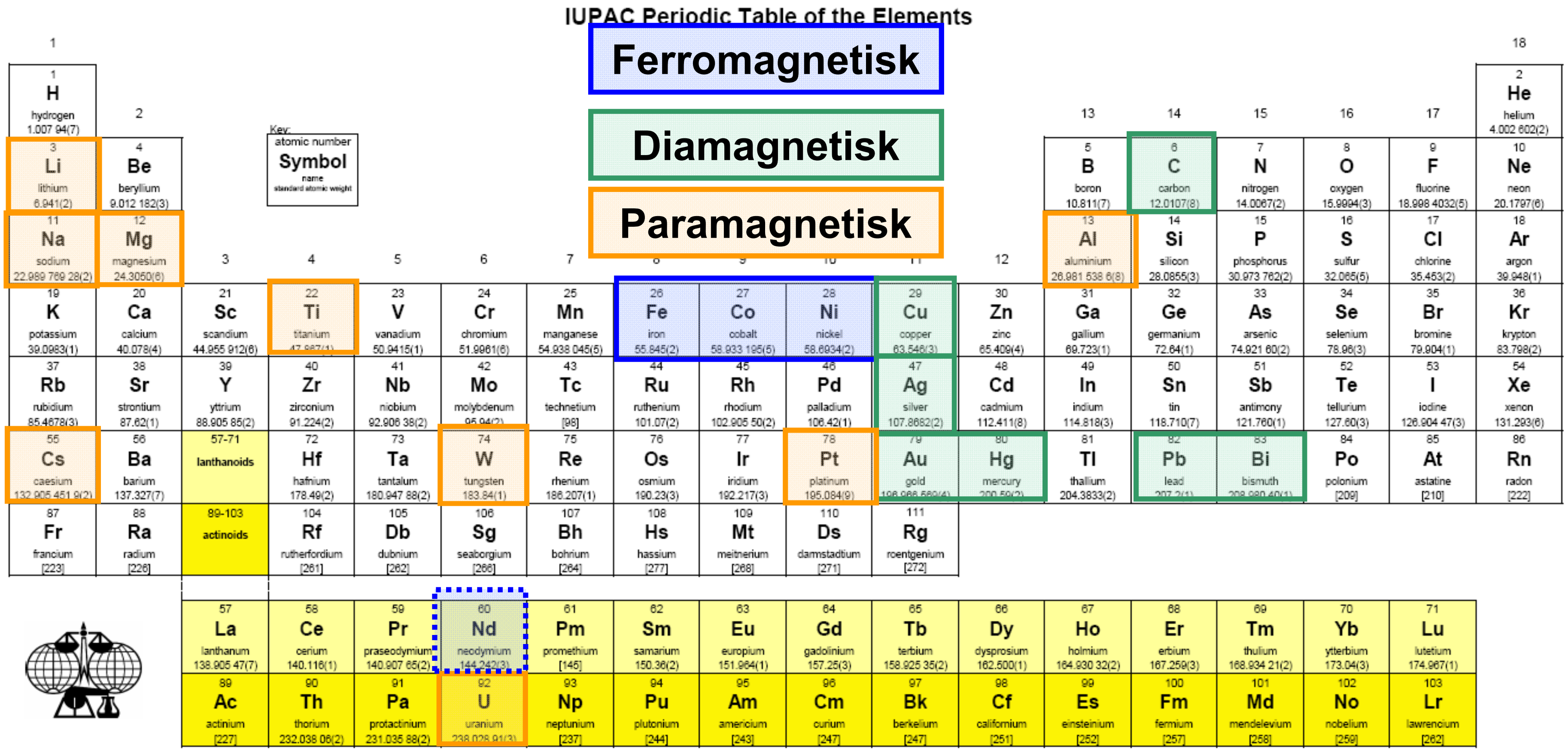
Middels *H*-felt:
Domener med magn.moment ***μ*** i samme retning som ***H*** vokser i størrelse



Sterke *H*-felt:
Magnetisk moment innen domener roterer til || ***H***

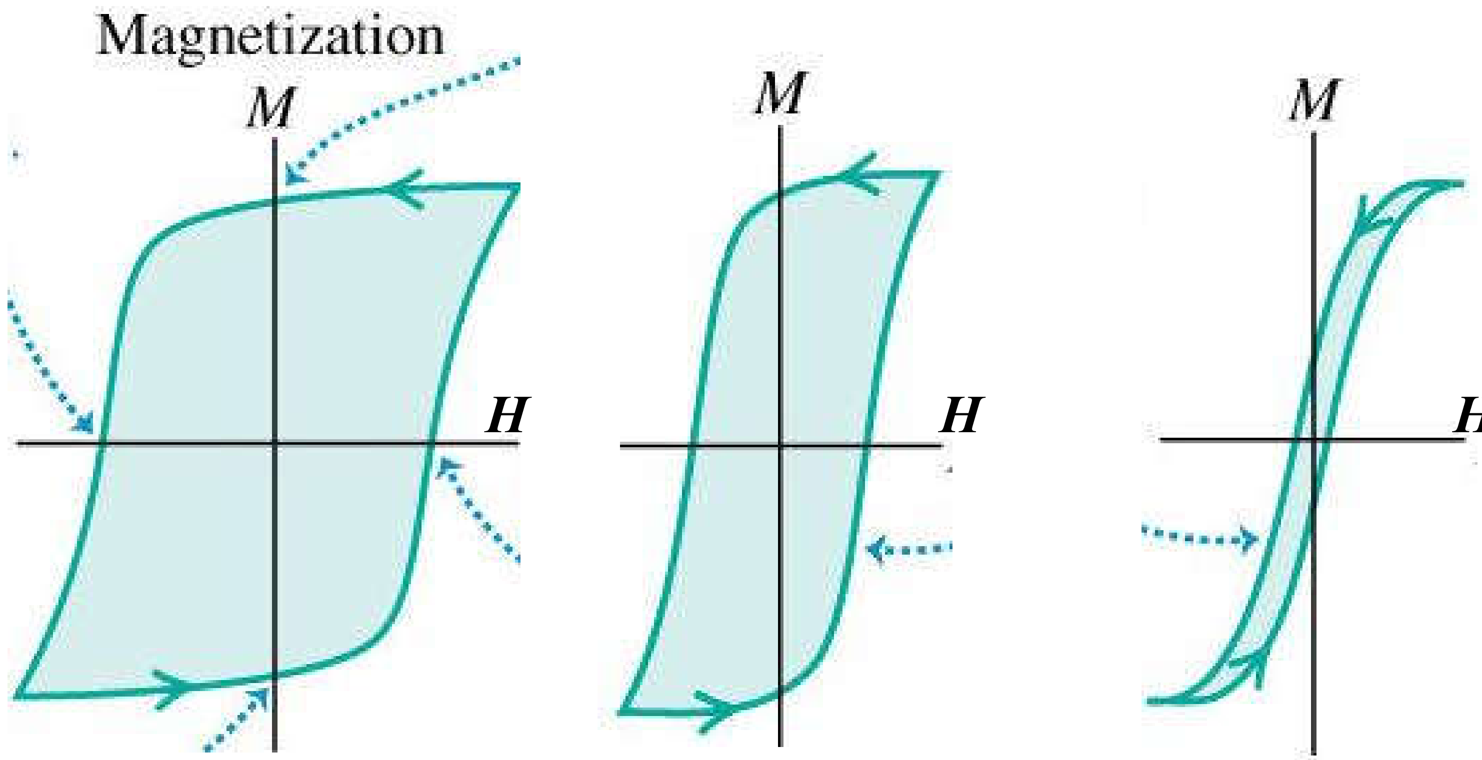
=> Metning

Fig: en.wikipedia.org/wiki/Magnetic_domain



Notes
- 'Aluminum' and 'cesium' are commonly used alternative spellings for 'aluminium' and 'caesium'.
- IUPAC 2005 standard atomic weights (mean relative atomic masses) are listed with uncertainties in the last figure in parentheses [M. E. Wieser, *Pure Appl. Chem.* 78, 2051 (2006)].
These values correspond to current best knowledge of the elements in natural terrestrial sources. For elements that have no stable or long-lived nuclides, the mass number of the nuclide with the longest confirmed half-life is listed between square brackets.
- Elements with atomic numbers 112 and above have been reported but not fully authenticated.

Ulike grader av hysterese i ferromagnetisk materiale



«Hardt» jern:
permanentmagneter

av/på-magneter
(eks. harddisk)

«Bløtt» jern:
tranformatorer

Y&F Figure 28.29

Hva vi har lært:

- Magnetisk feltstyrke: $\boldsymbol{H} = \boldsymbol{B}/\mu_0$ (i tomrom)

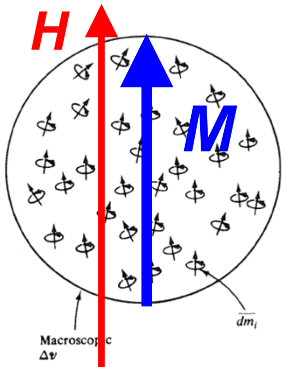
- Magnetisering, definisjon: $\boldsymbol{M} = \sum \boldsymbol{\mu}$ / volum
- Magnetisering, eksperimentelt: $\boldsymbol{M} = \chi_m \boldsymbol{H}$

- Totalt ***B***-felt i magnetisk materiale:

$$\boldsymbol{B} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{M}$$
$$= \mu_0 \boldsymbol{H} + \mu_0 \chi_m \boldsymbol{H}$$
$$= \mu_0 \mu_r \boldsymbol{H},$$

Kraftig forsterkning av *B*-feltet i ferromagn. materiale

relativ permeabilitet: $\mu_r = \chi_m + 1$

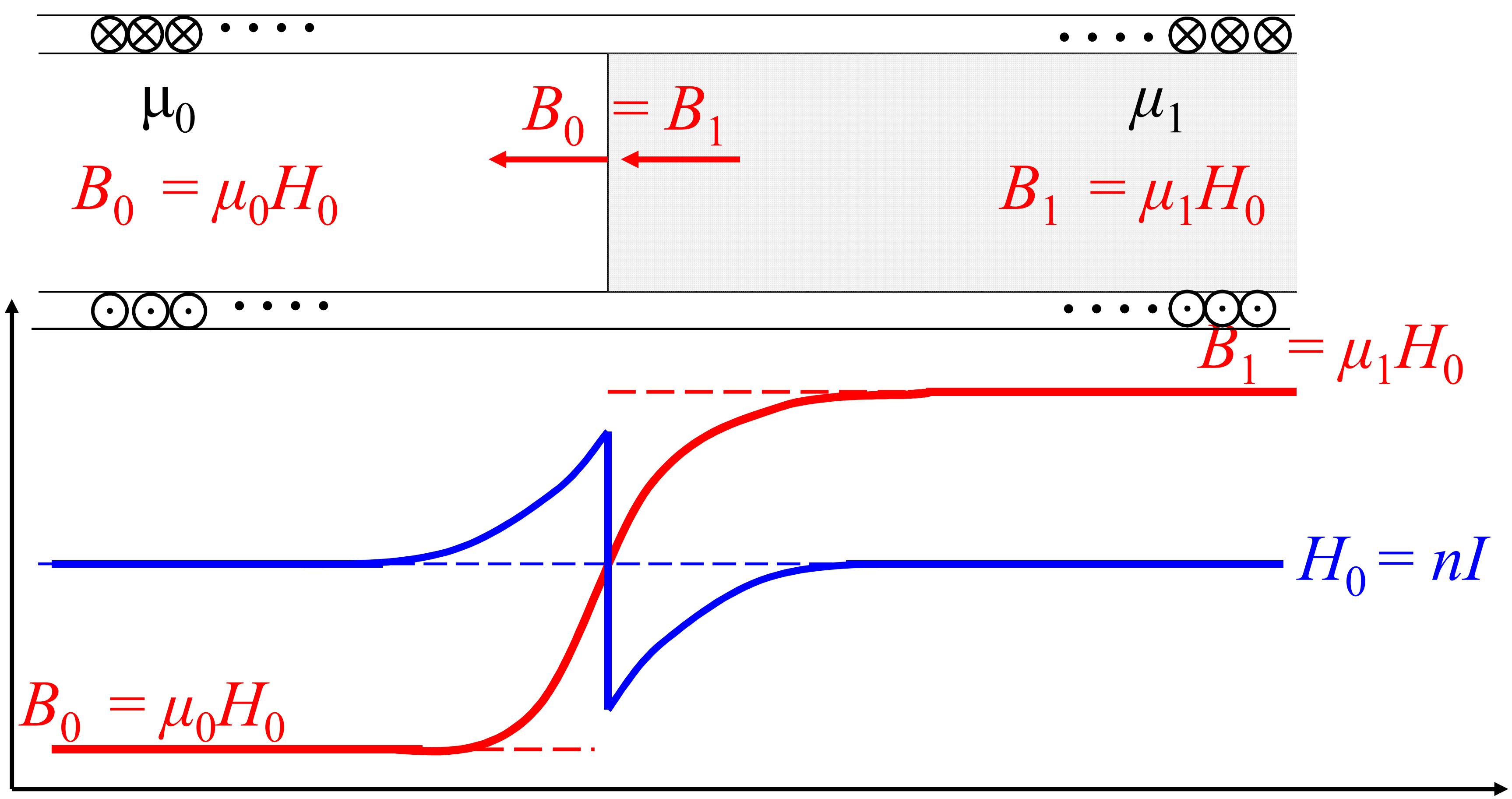


- Amperes lov på ny, enkel form:

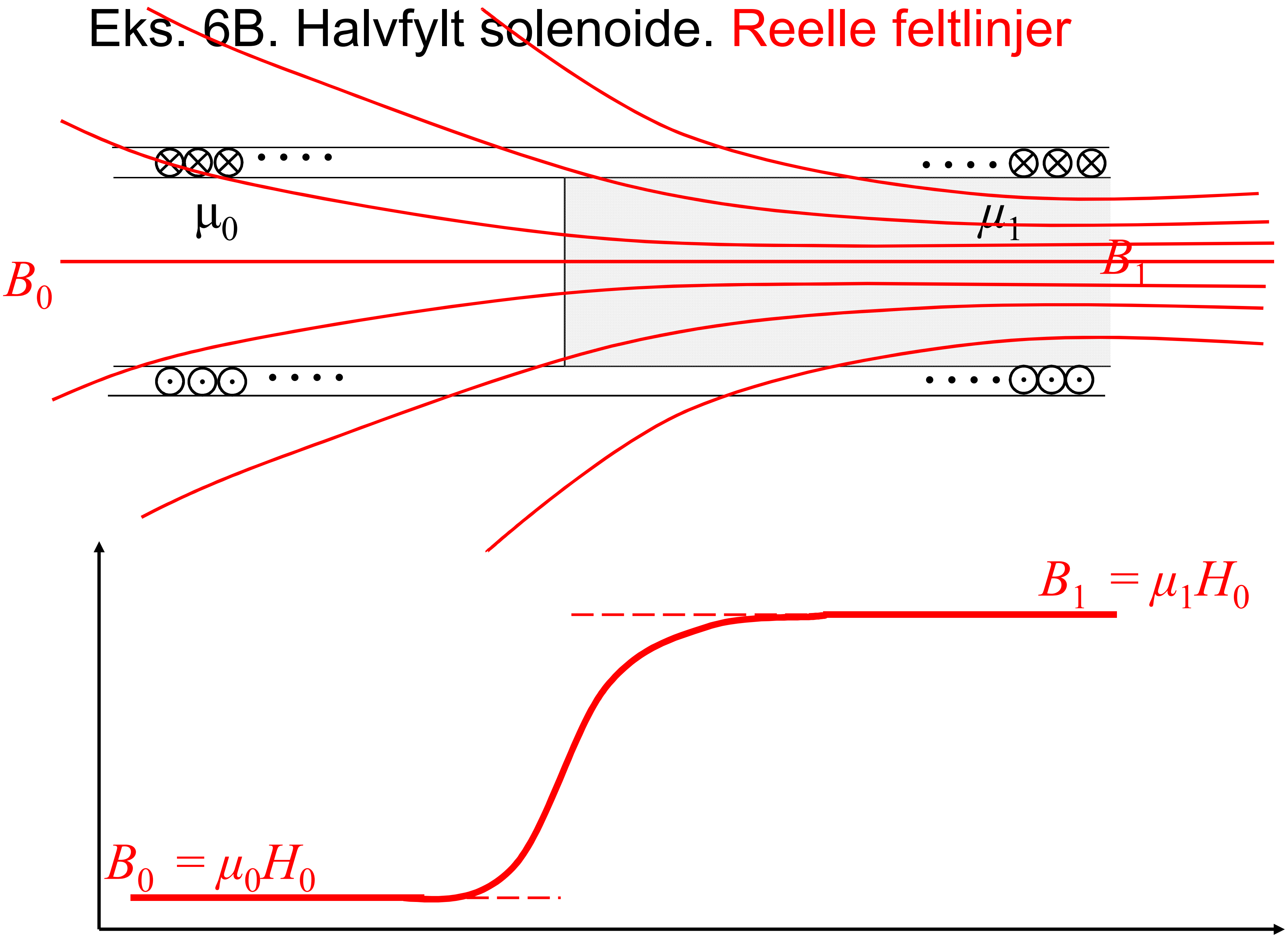
$$\int \boldsymbol{B} \cdot d\boldsymbol{s} = \mu_0 I \quad \Longleftrightarrow \quad \int \boldsymbol{H} \cdot d\boldsymbol{s} = I$$

curl $\boldsymbol{B} = \mu_0 \boldsymbol{J}$ <=> curl $\boldsymbol{H} = \boldsymbol{J}$

Eks. 6B. Halvfylt solenoide



Eks. 6B. Halvfylt solenoide. Reelle feltlinjer



Kontinuitetskrav over grenseflater (skille i μ_r):

1) $B_\perp$ kontinuerlig

2) $H_\perp$ diskontinuerlig (faktor μ_r)

3) $H_\parallel$ kontinuerlig

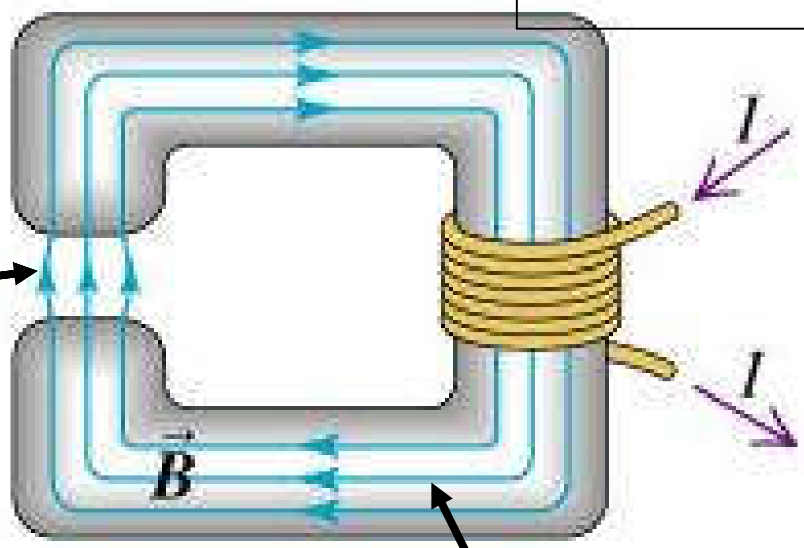
4) $B_\parallel$ diskontinuerlig (faktor μ_r)

Eks. 6C. Langsfylt solenoide.

= Øving 12, opg 1
og Eks. 2012 opg. 5.

Eks. 7 Luftgap i magnet

= øving 12, opg 2.



Lite gap:

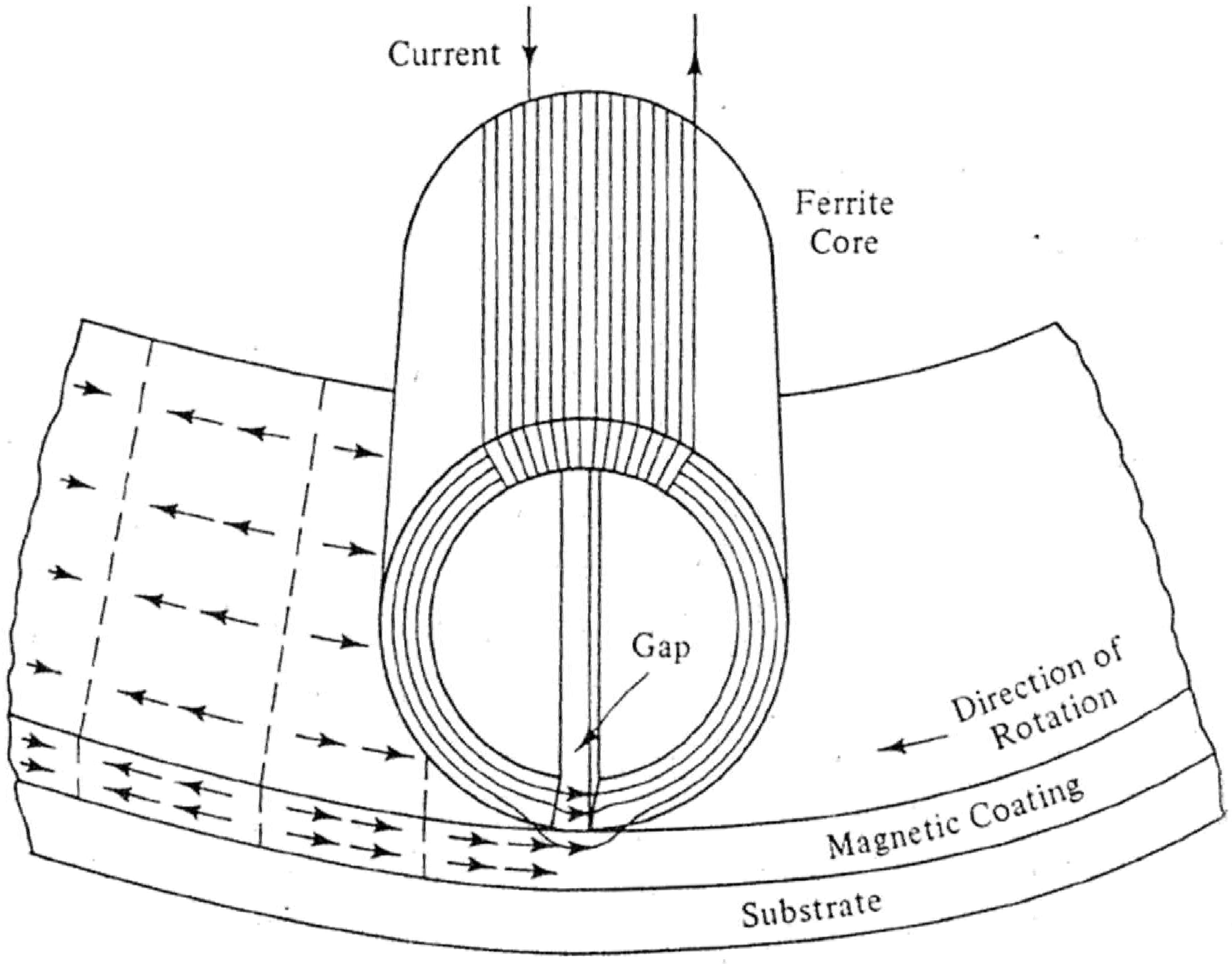
$B_{\text{luft}} \approx B_{\text{jern}}$

Stort gap:

B_{luft} mindre

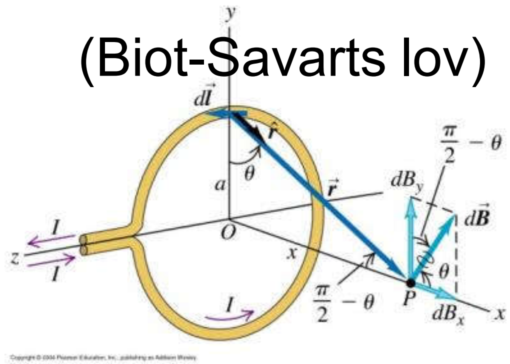
B-feltlinjer
følger jernet

Magnetgap til bruk for å skrive på harddisk, videotape og lignende



Kap. 28: Oppsummering:
Kilde til magnetisk felt

- Bevegelse av ladninger er kilde for magnetfelt ***B***
  - Enkeltladning i bevegelse: $$\vec{B} = \frac{\mu_0}{4\pi}\frac{q\vec{v}\times\hat{r}}{r^2}$$
  - Strøm i leder: $$\mathrm{d}\vec{B} = \frac{\mu_0}{4\pi}\frac{I\mathrm{d}\vec{s}\times\hat{r}}{r^2}$$ (Biot-Savarts lov)



- Magnetfelt ***B*** kan finnes ved integrasjon over leder fra Biot-Savarts lov
  -- eller ved bruk av:
- Amperes lov:

$$\oint \boldsymbol{B}\cdot \mathrm{d}\boldsymbol{s} = \mu_0 I \qquad\qquad \oint \boldsymbol{H}\cdot \mathrm{d}\boldsymbol{s} = I$$

der I er strøm innenfor den lukkede integrasjonsvegen.

Differensialform: curl $\boldsymbol{B} = \mu_0 \boldsymbol{J}$ curl $\boldsymbol{H} = \boldsymbol{J}$

- Viktige anvendelser: Rett leder, solenoide, m.m.

Kap. 28: Oppsummering:
Magnetiske materialer [mer i Notat 2]

- Materialer kan magnetiseres: $\boldsymbol{M} = \chi_m \boldsymbol{H}$
  - Diamagnetiske: χ_m liten, negativ
  - Paramagnetiske: χ_m liten, positiv
  - Ferromagnetiske: χ_m **stor** positiv

- Strømmer skaper magnetisk feltstyrke $\boldsymbol{H}$ og flukstetthet:

  $\boldsymbol{B} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{M} = \mu_0 \boldsymbol{H} + \mu_0 \chi_m \boldsymbol{H} = \mu_0 \mu_r \boldsymbol{H}$

  .. altså avhengig av relativ permeabilitet μ_r og dermed av materialet.

- I alle tidligere formler kan vi erstatte μ_0 med $\mu = \mu_0 \mu_r$

- Kontinuitetskrav over grenseflater (skille i μ_r): [Mer i Notat 6]

  $B_\perp$ kontinuerlig $B_\parallel$ diskontinuerlig

  $H_\perp$ diskontinuerlig $H_\parallel$ kontinuerlig

Maxwells likninger i Notat 4

Statikk

Integralform | Differensialform

$$\oint \vec{D} \cdot \mathrm{d}\vec{A} = Q$$

Gauss' lov ***D***

$$\vec{\nabla} \cdot \vec{D} = \rho$$

$$\oint \vec{B} \cdot \mathrm{d}\vec{A} = 0$$

Gauss' lov ***B***

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\oint \vec{H} \cdot \mathrm{d}\vec{\ell} = I + \frac{\partial \Phi}{\partial t}$$

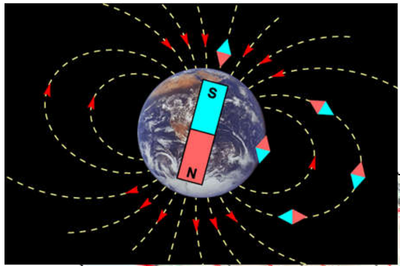
Amperes lov

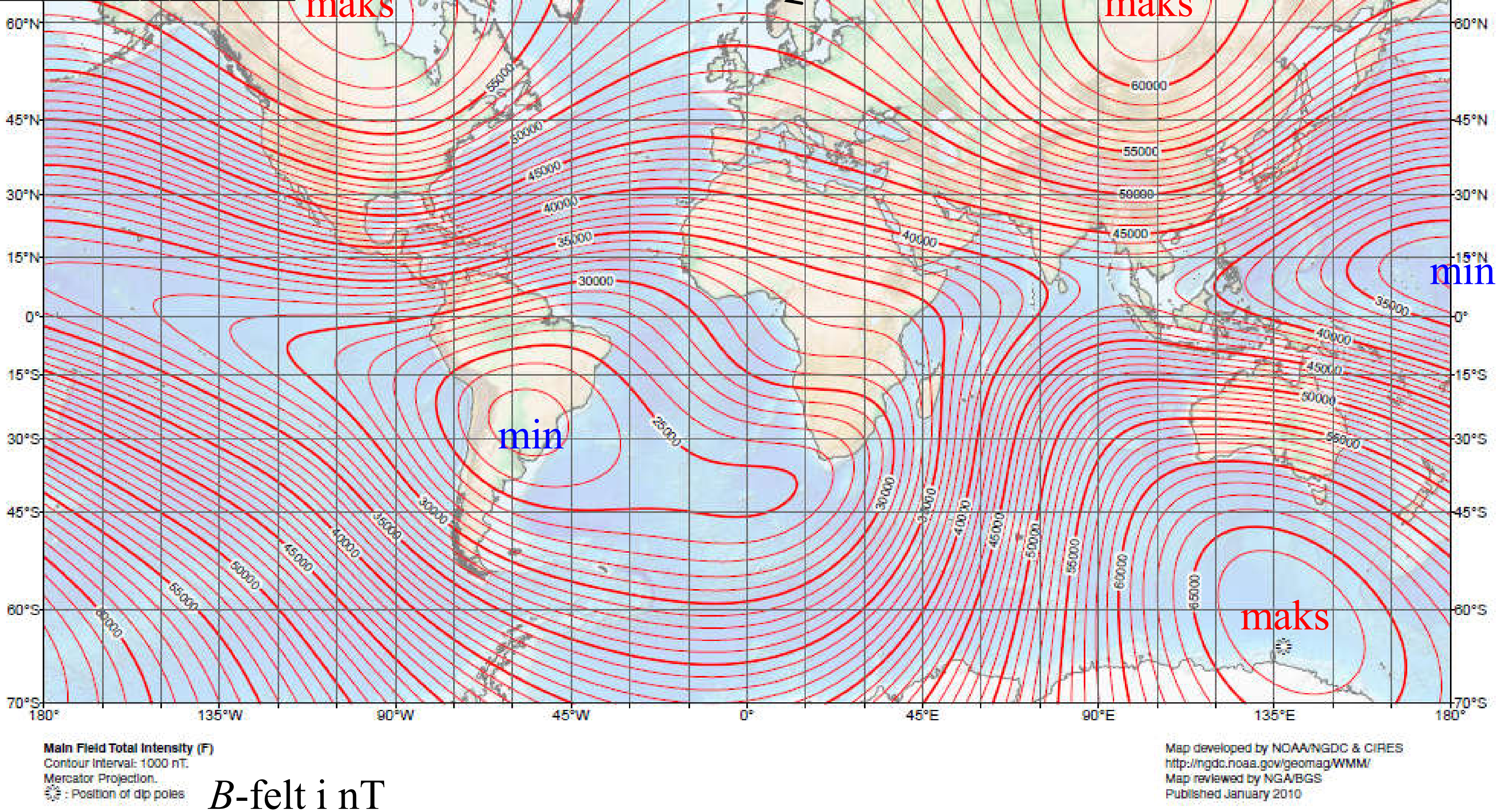
$$\vec{\nabla} \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$

$$\oint \vec{E} \cdot \mathrm{d}\vec{\ell} = 0 \quad \left(- \frac{\partial \Phi_B}{\partial t}\right)$$

Faradays lov

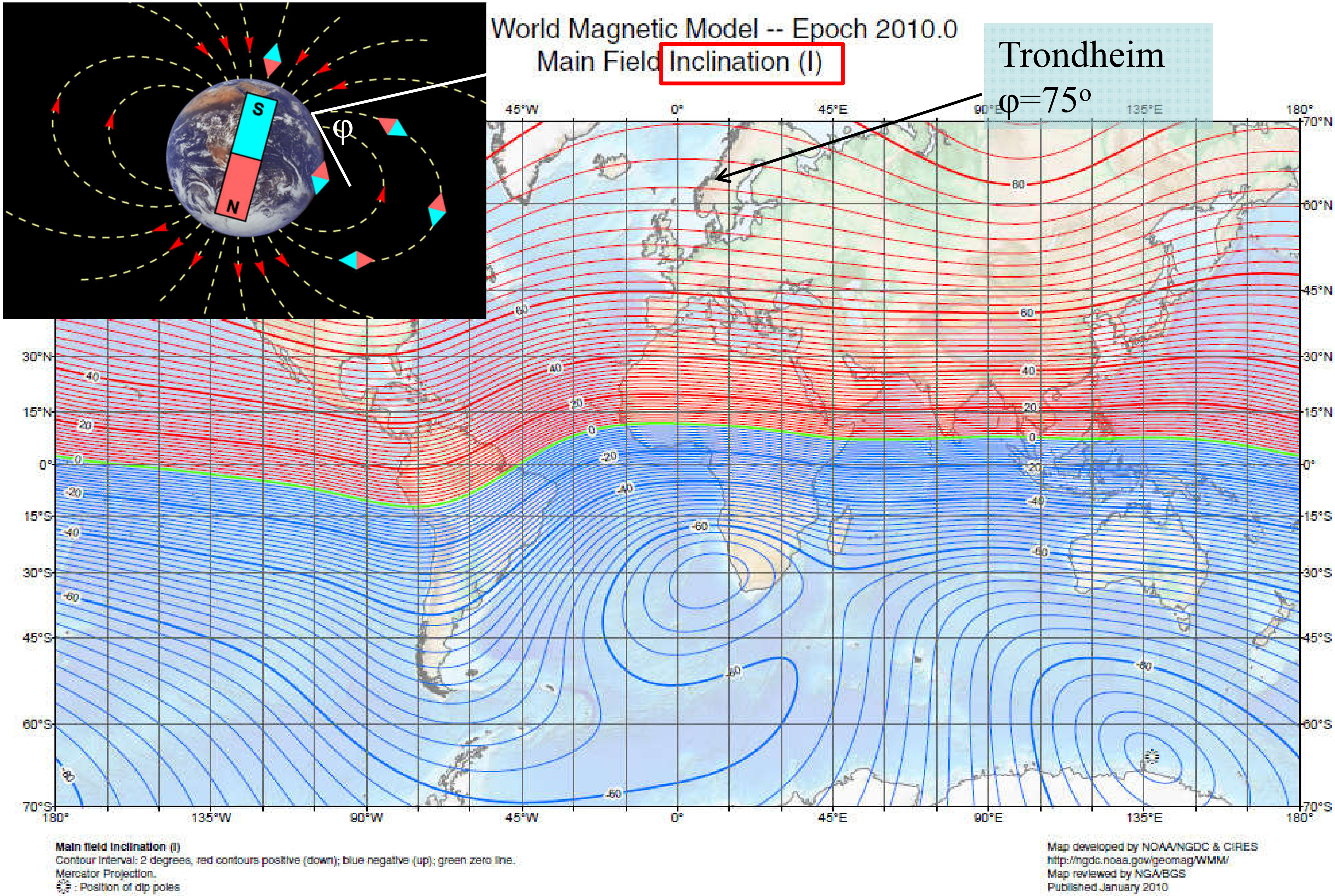
$$\vec{\nabla} \times \vec{E} = 0 \quad \left(- \frac{\partial \vec{B}}{\partial t}\right)$$





B-felt i nT

Fra: en.wikipedia.org/wiki/Earth%27s_magnetic_field



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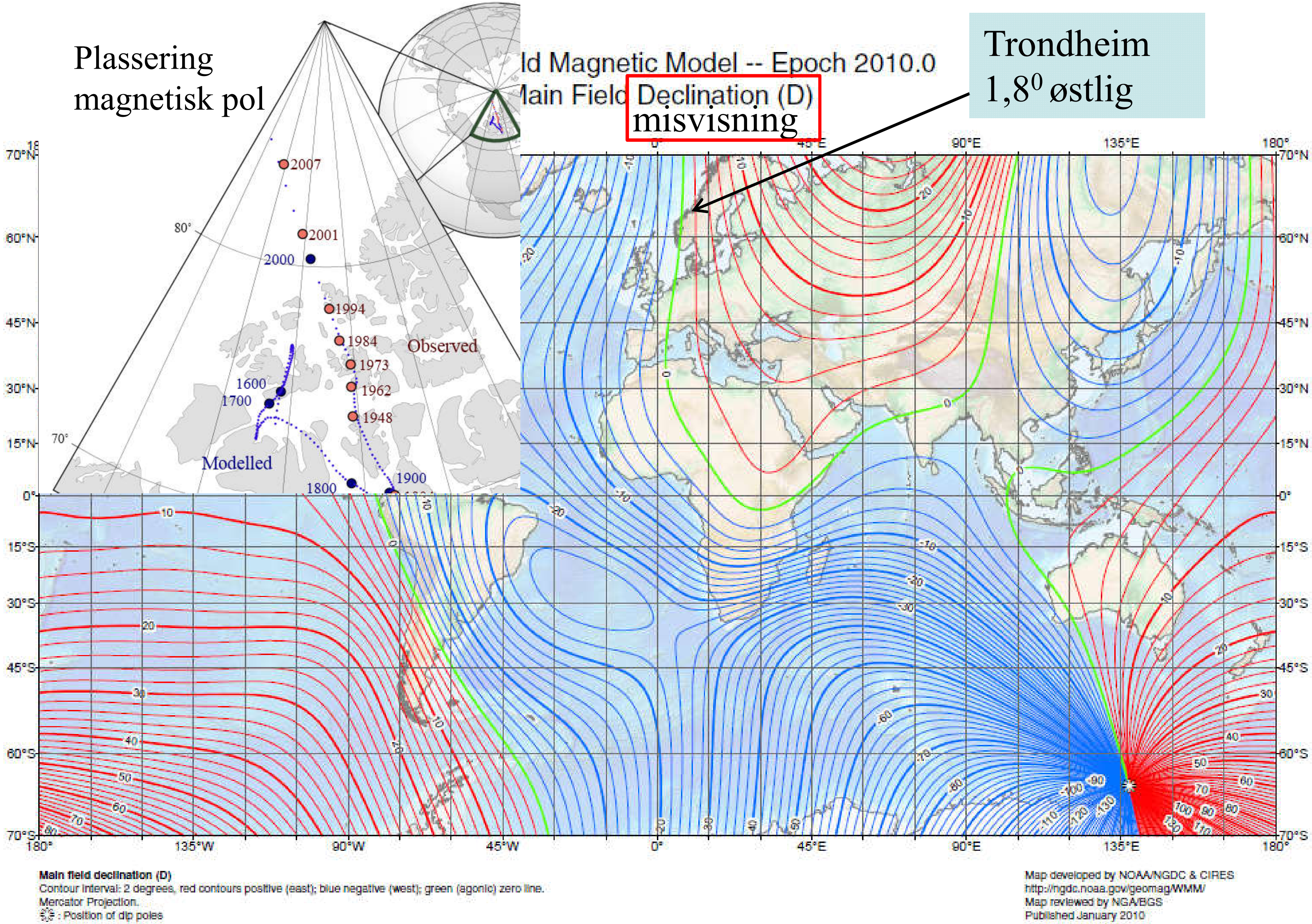

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