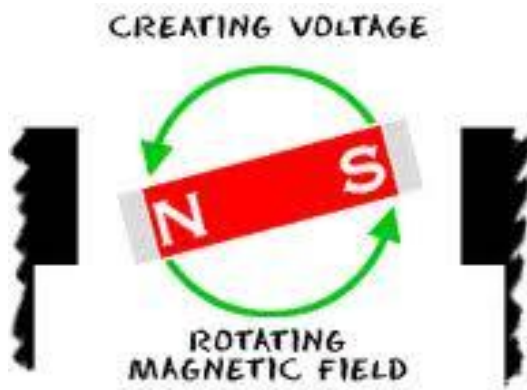


# elektromagnetická indukce



# statická a dynamická pole

statická pole:  
elektrické

$$\oiint_S \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_0}$$

$$\oint_C \vec{E} \cdot d\vec{s} = 0$$

magnetické

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

$$\oiint_S \vec{B} \cdot d\vec{S} = 0$$

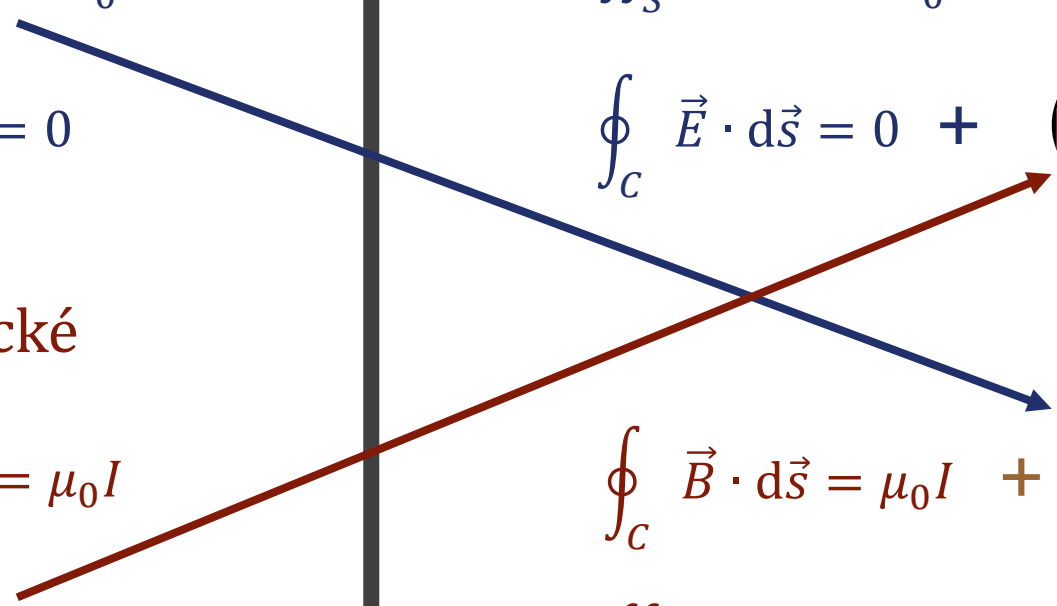
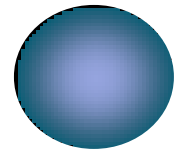
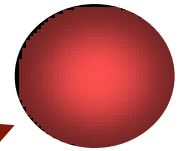
dynamické pole:  
elektromagnetické

$$\oiint_S \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_0}$$

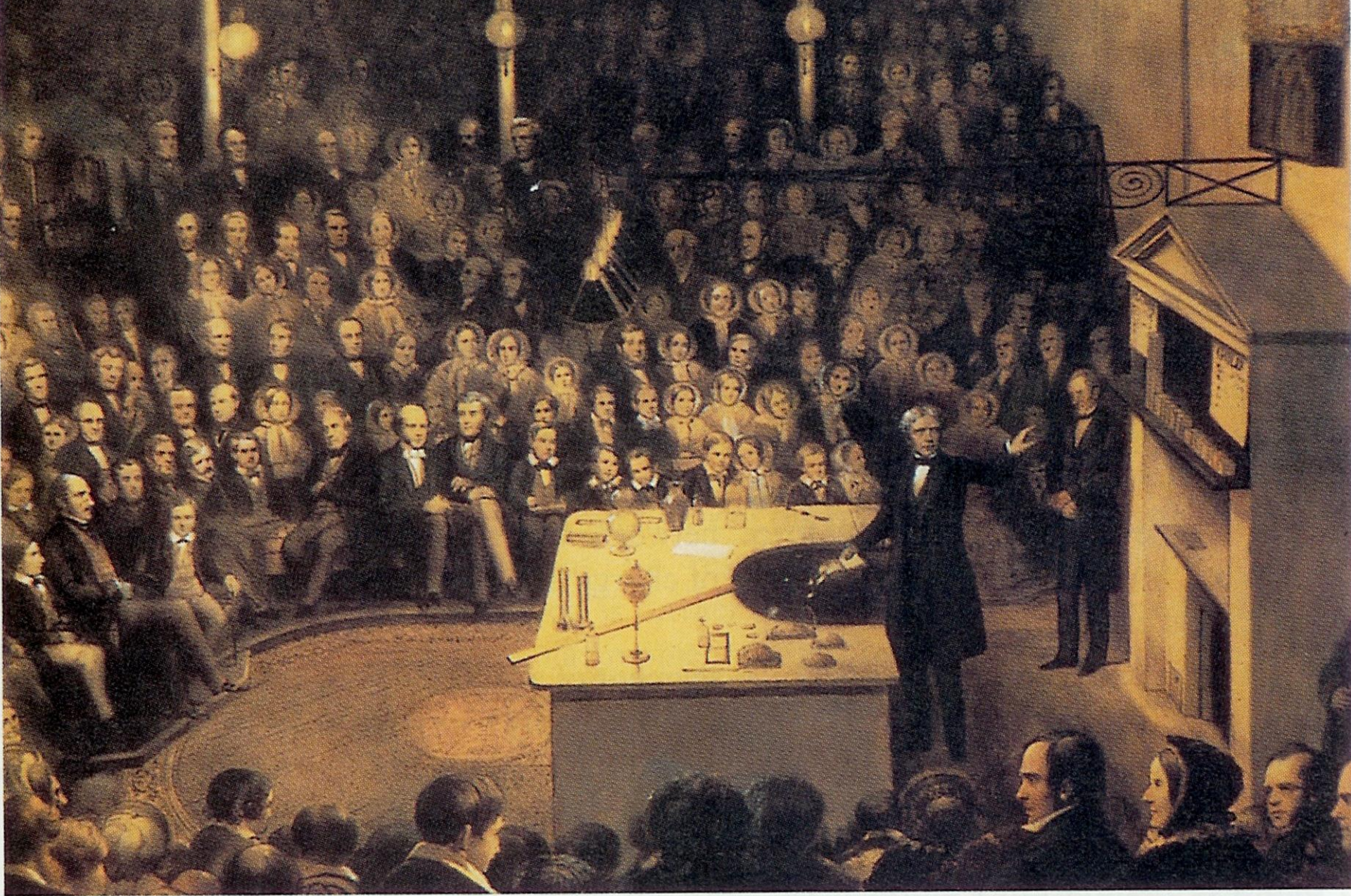
$$\oint_C \vec{E} \cdot d\vec{s} = 0 +$$

$$\oint_C \vec{B} \cdot d\vec{s} = \mu_0 I +$$

$$\oiint_S \vec{B} \cdot d\vec{S} = 0$$



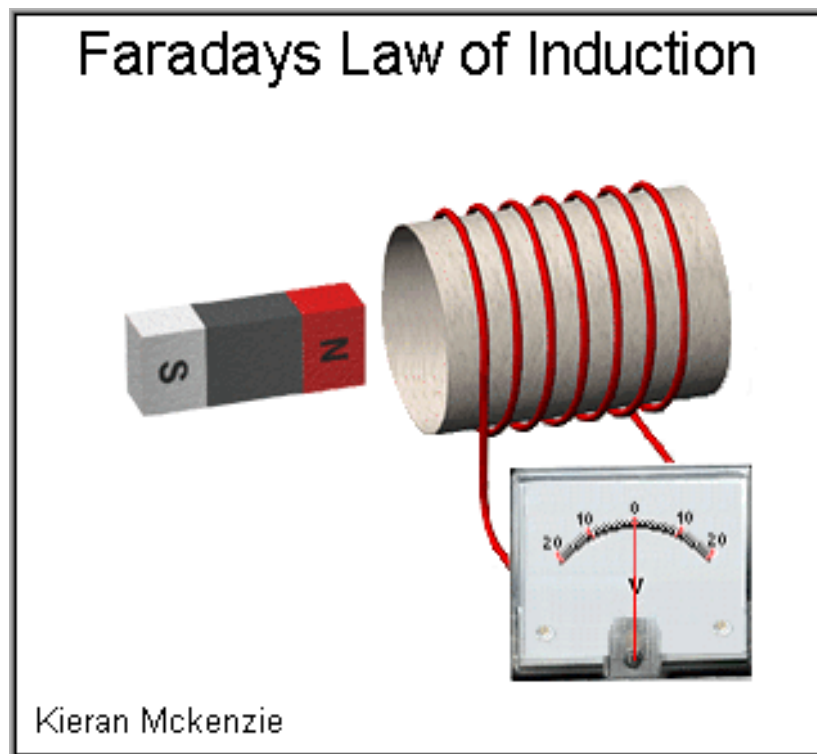




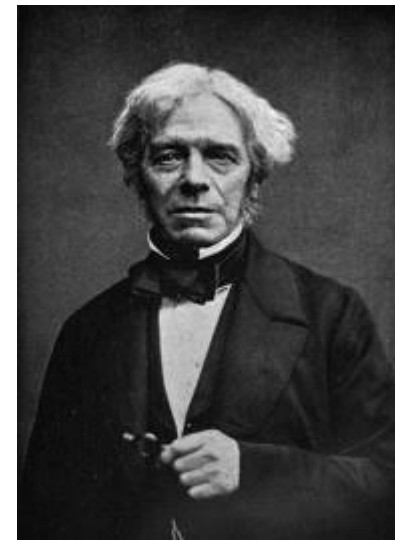
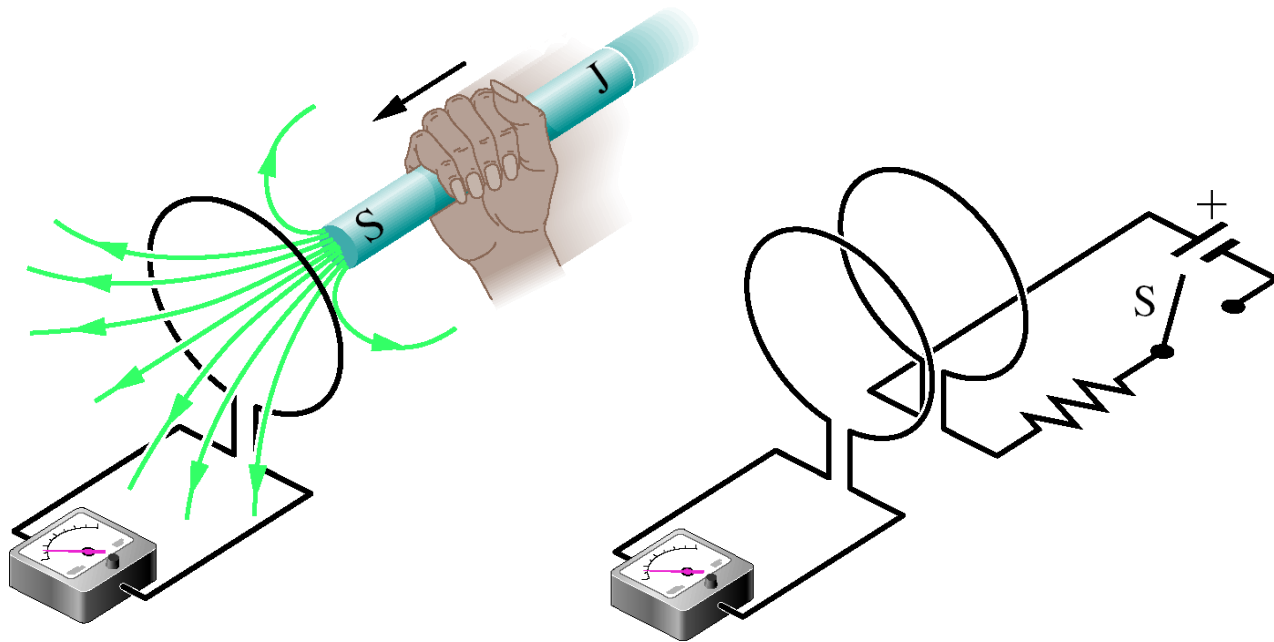
*Michael Faraday delivering one of his famous public lectures in 1856. These lectures earned him great popular success.*



# jev elektromagnetické indukce



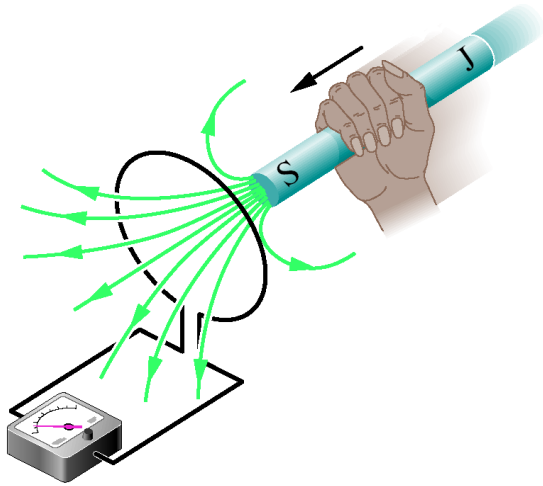
# formulace M. Faradaye



Michael Faraday:

Elektromotorické napětí (emn) se ve smyčce indukuje při **změně počtu indukčních čar**, které procházejí smyčkou.

# Faradayův zákon elektromagnetické indukce




velikost emn ve vodivé smyčce je rovna **rychlosti** změny magnetického indukčního toku procházejícího touto smyčkou.

$$\mathcal{E} = - \frac{d\Phi_B}{dt}$$

$$\longleftarrow \Phi_B = \iint \vec{B} \cdot d\vec{S}$$

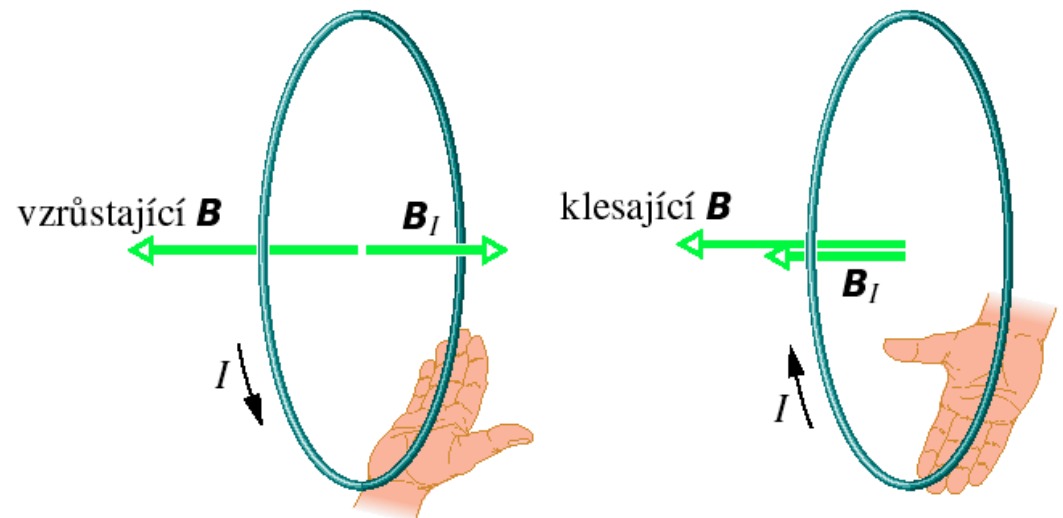
# Lenzův zákon

$$\varepsilon = - \frac{d\Phi_B}{dt}$$


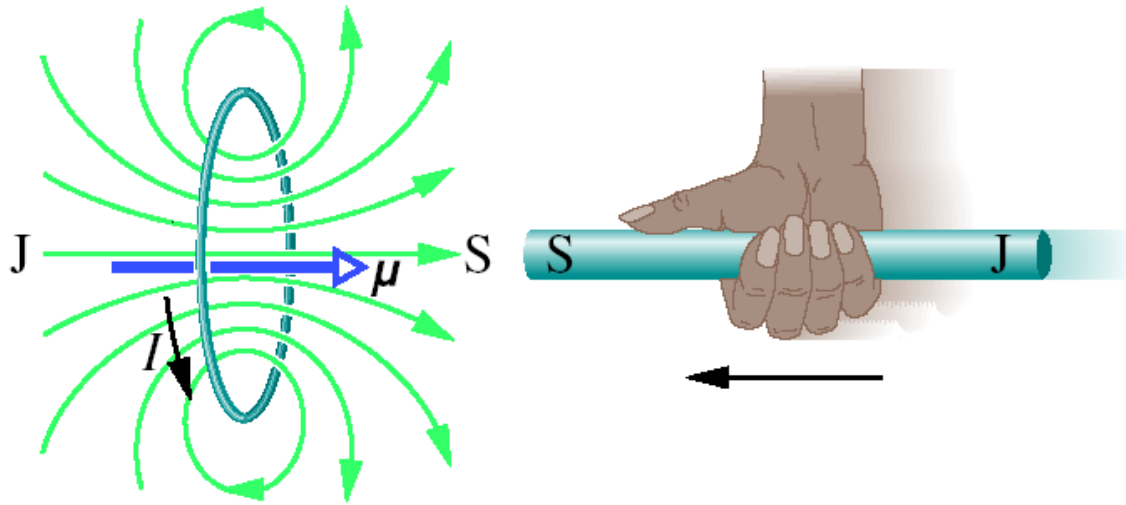
indukovaný proud ( $I$ ) má takový směr, že magnetické pole ( $B_I$ ) tímto proudem vzbuzené působí **proti změně** magnetického pole ( $B$ ), která proud indukovala



Emil Lenz  
1804 - 1865



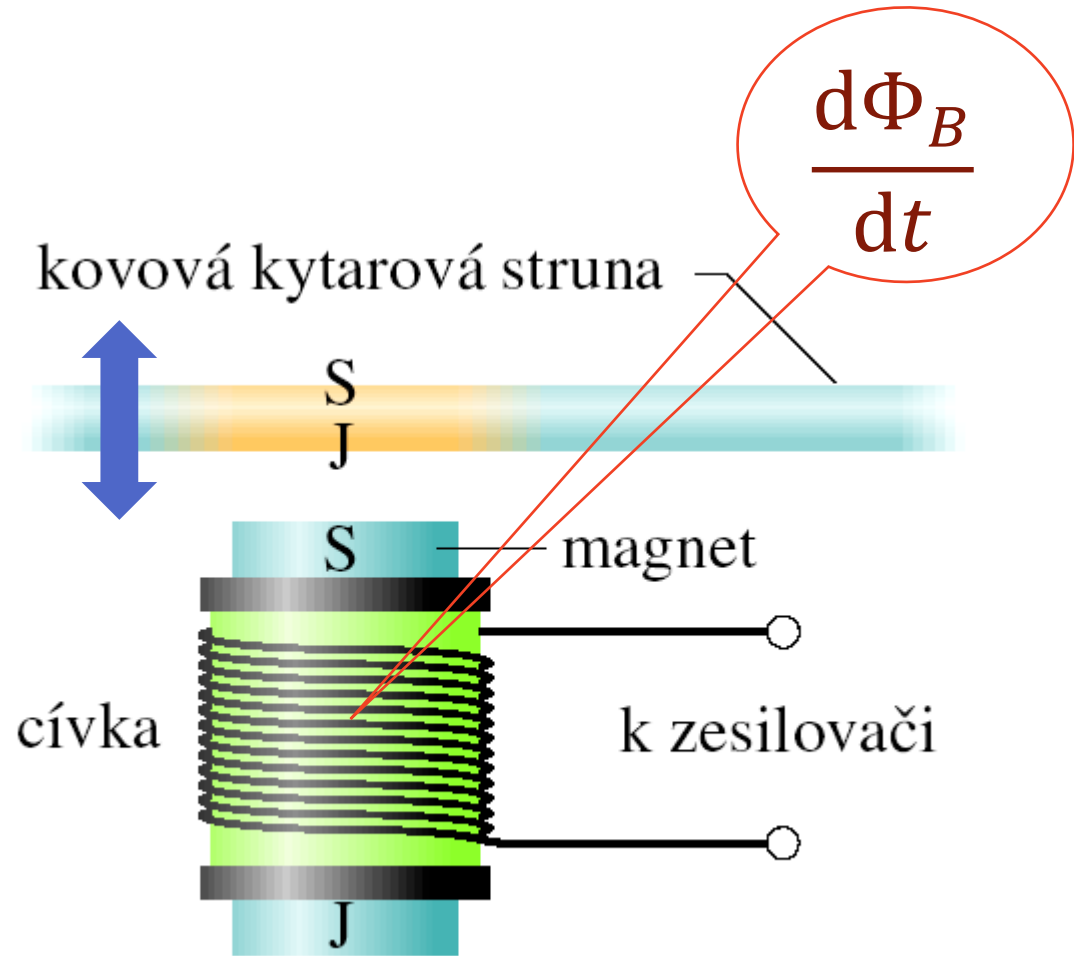
# Lenzův zákon



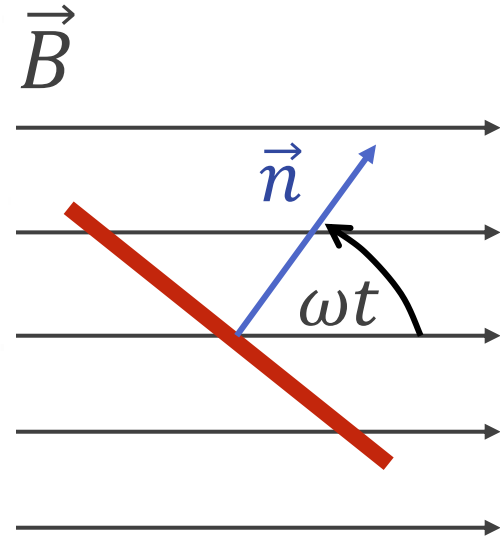
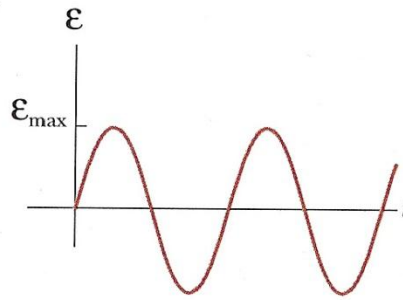
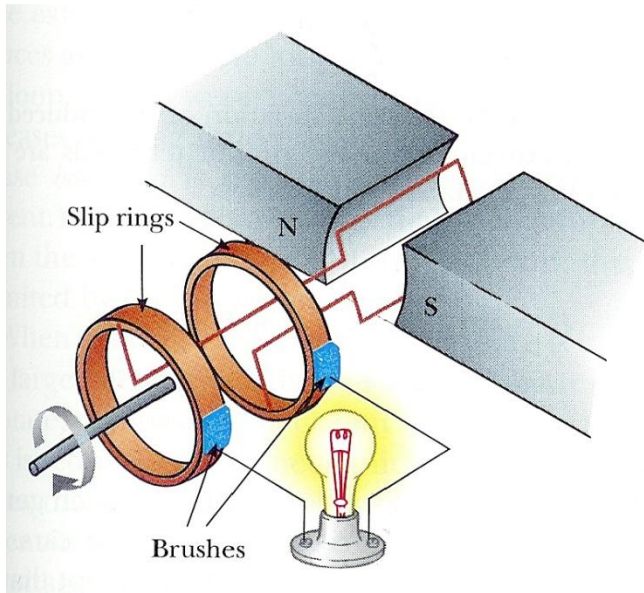
**Obr. 31.4** Použití Lenzova zákona. Pohybujeme-li magnetem ke smyčce, indukuje se ve smyčce proud  $I$  proti směru otáčení hodinových ručiček; tento proud vytváří vlastní magnetické pole s magnetickým dipólovým momentem  $\mu$  takovým, že brání přibližování magnetu.



# aplikace: elektrická kytara



# aplikace: výroba elektřiny



$$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BS \cos \omega t) = BS\omega \sin \omega t$$

# indukce a přenosy energie

$$P_{\text{tep}} = I^2 R = \frac{(BLv)^2}{R}$$

$$\varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}(BLx) = BLv$$

$$I = \frac{\varepsilon}{R} = \frac{BLv}{R}$$

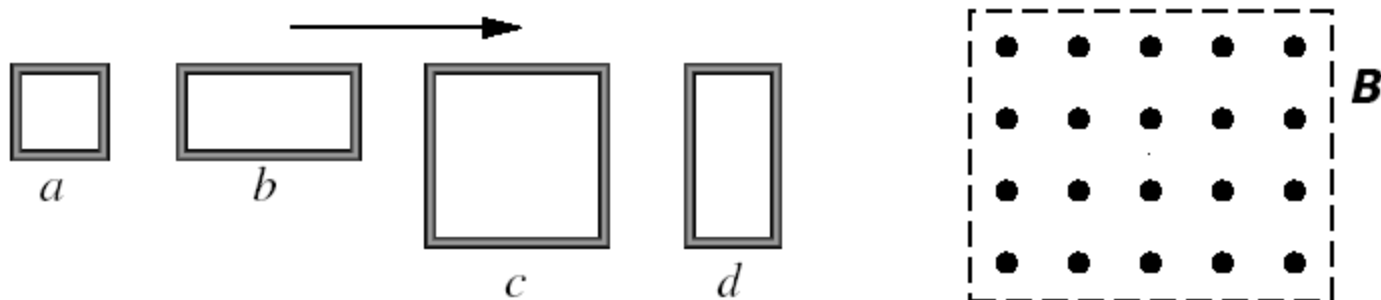
$$F = ILB = \frac{B^2 L^2 v}{R}$$

$$P_{\text{mech}} = vF = \frac{(BLv)^2}{R}$$

The diagram illustrates a rectangular rod of length  $L$  moving with velocity  $v$  to the right in a uniform magnetic field  $B$  directed into the page (indicated by green 'x' marks). The rod is part of a circuit with resistance  $R$ . The induced EMF is  $\varepsilon = BLv$  and the induced current is  $I = \frac{BLv}{R}$ . The magnetic force on the rod is  $F = ILB = \frac{B^2 L^2 v}{R}$ . The mechanical power input is  $P_{\text{mech}} = vF = \frac{(BLv)^2}{R}$ , which is equal to the thermal power dissipated in the resistor  $P_{\text{tep}} = I^2 R = \frac{(BLv)^2}{R}$ .

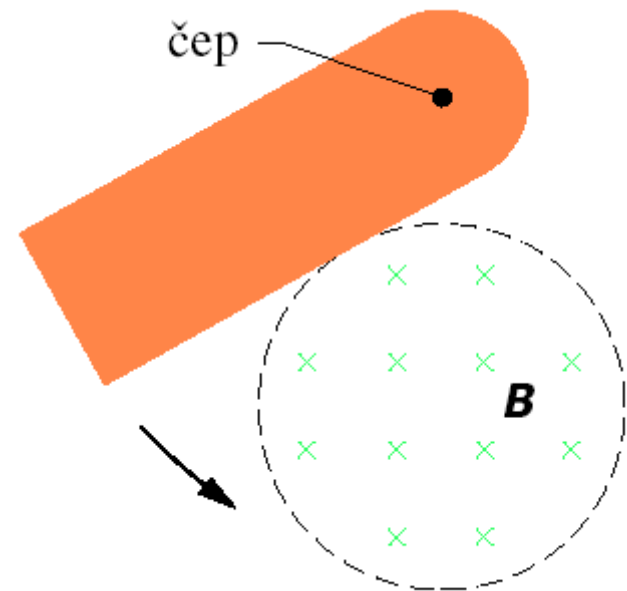
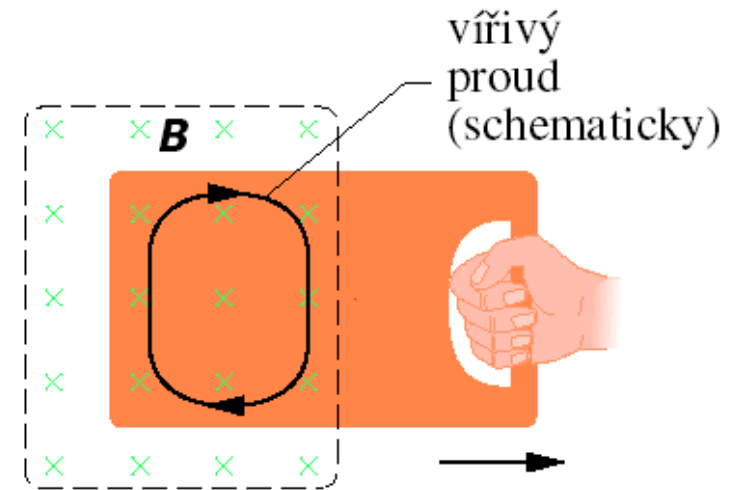
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**KONTROLA 3:** Obrázek ukazuje čtyři vodivé smyčky s délkami stran  $L$  nebo  $2L$ . Všechny smyčky budou vnikat stejnou stálou rychlostí do oblasti homogenního magnetického pole  $\mathbf{B}$  (vystupujícího kolmo ze stránky). Seřadte tyto čtyři smyčky podle velikosti emn, indukovaného během vstupu do pole, největší uveďte jako první.

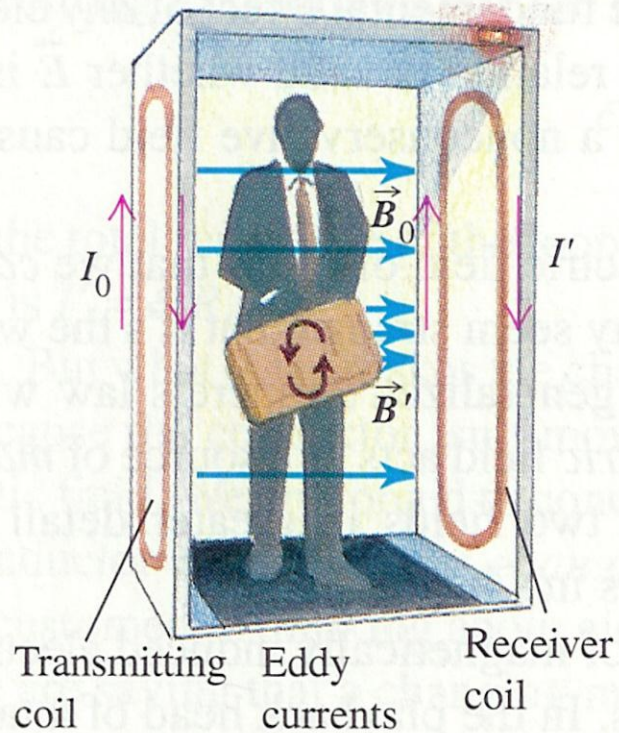




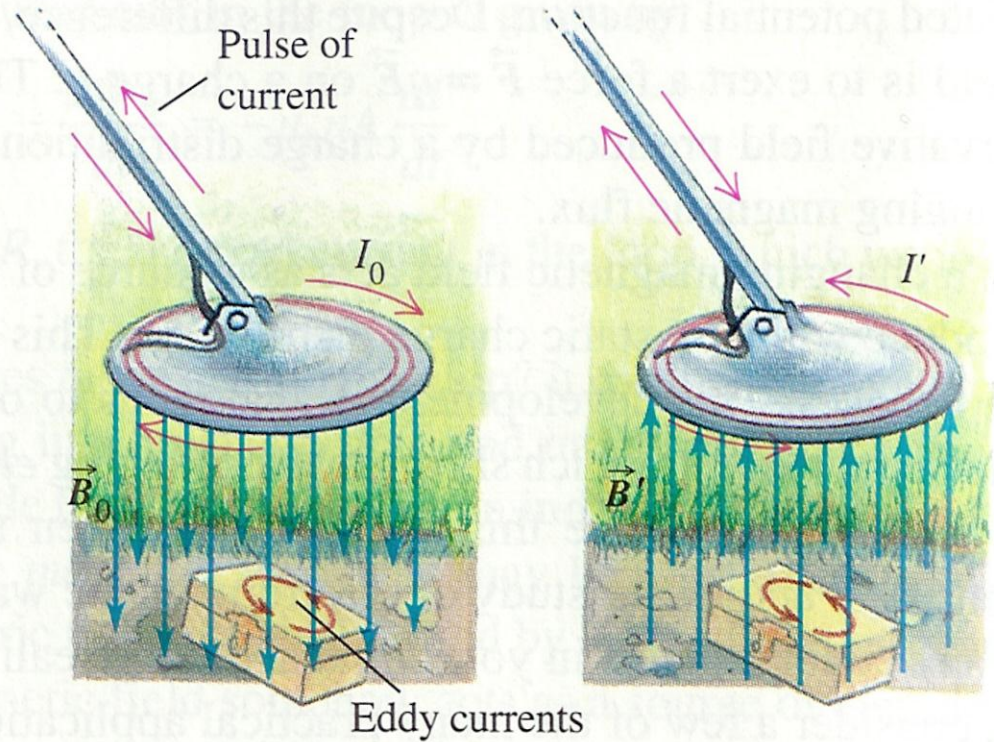
# vířivé proudy



# vířivé proudy: aplikace



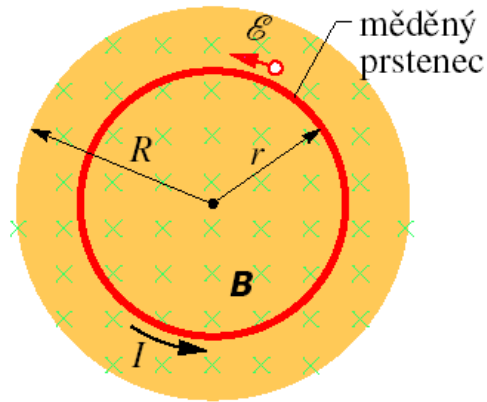
(a)



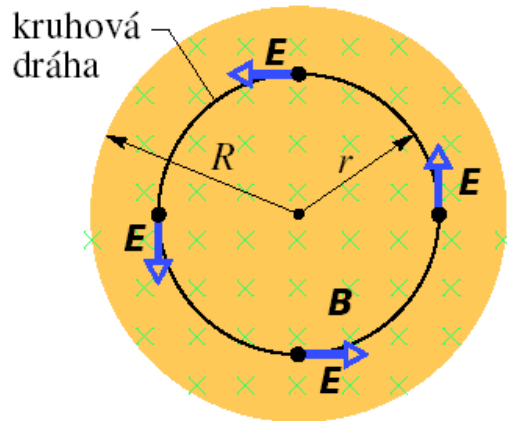
(b)

**30-20** (a) A metal detector at an airport security checkpoint generates an alternating magnetic field  $\vec{B}_0$ . This induces eddy currents in a conducting object carried through the detector. The eddy currents in turn produce an alternating magnetic field  $\vec{B}'$ , and this field induces a current in the detector's receiver coil. (b) Portable metal detectors work on the same principle.

# indukované elektrické pole

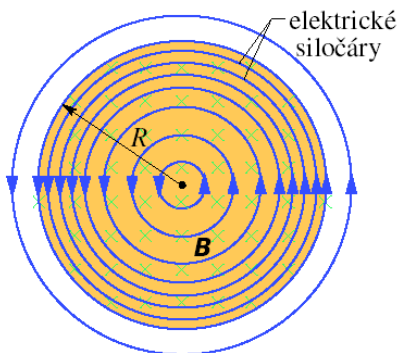


- na elektrony **v klidu** působí síla – **elektrická**
- měnící se magnetické pole vytváří pole **elektrické**
- vzhledem k symetrii musí mít směr **tečny ke kružnici** – (radiální složka nulová – Gaussův zákon)
- práce při jednom oběhu náboje  $Q_0$ :



$$W = Q_0 \oint_C \vec{E} \cdot d\vec{s} = Q_0 \mathcal{E}$$

$$\mathcal{E} = - \frac{d\Phi_B}{dt}$$



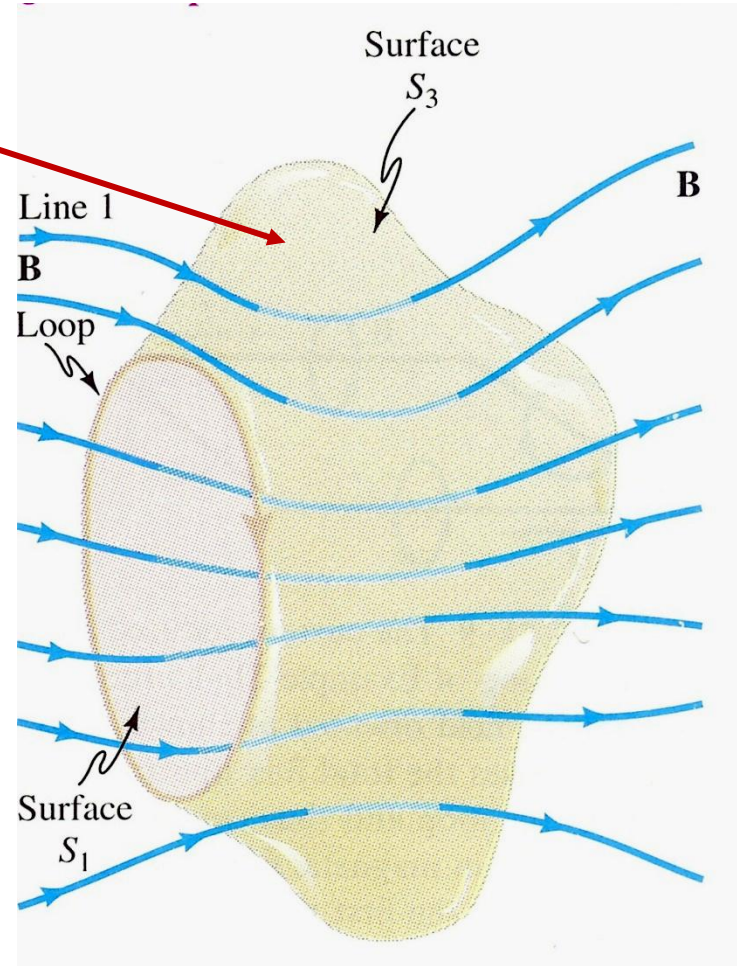
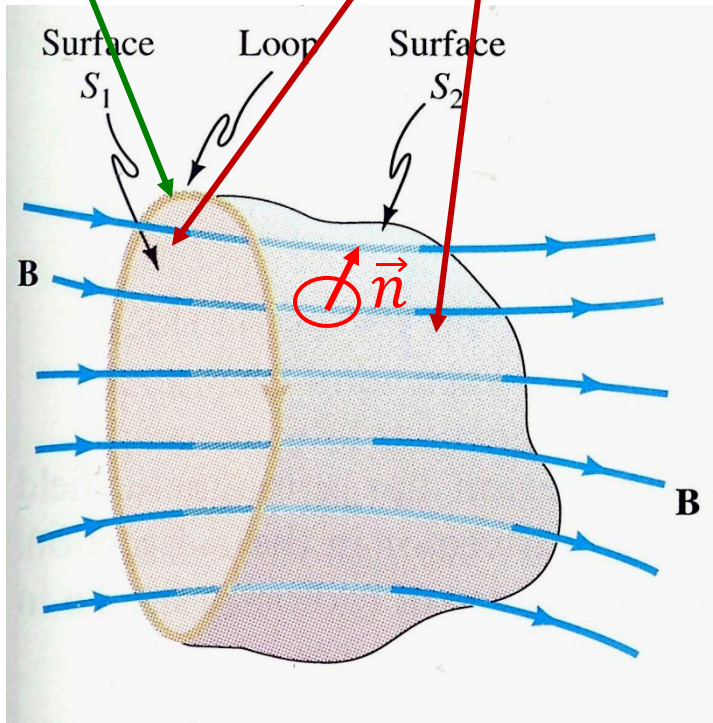
$$\oint_C \vec{E} \cdot d\vec{s} = - \frac{d}{dt} \iint_{S(C)} \vec{B} \cdot d\vec{S} \neq 0$$

nelze zavést elektrický potenciál!



# orientace křivky a plochy

$$\oint_C \vec{E} \cdot d\vec{s} = -\frac{d}{dt} \iint_{S(C)} \vec{B} \cdot d\vec{S}$$



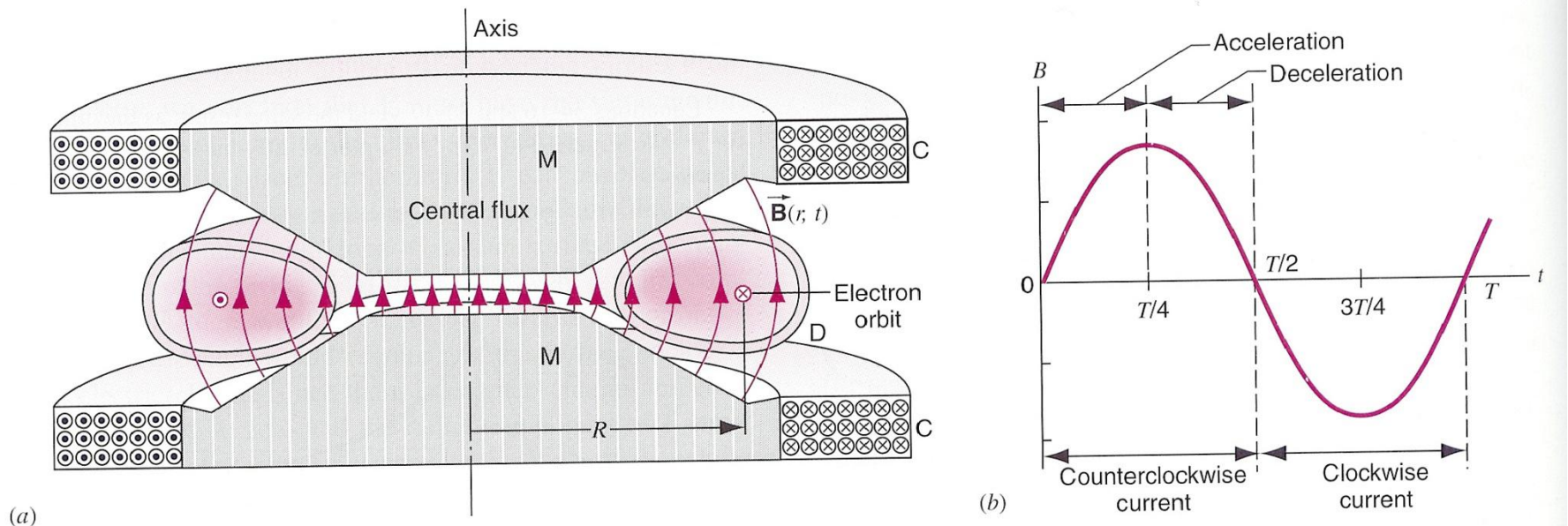


# betatron

elektrony o energii 100 MeV ( $v = 0.999987 c$ )

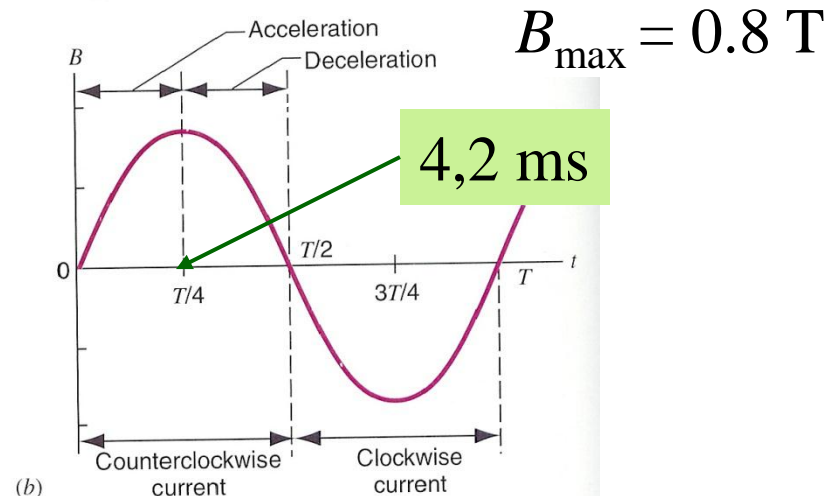
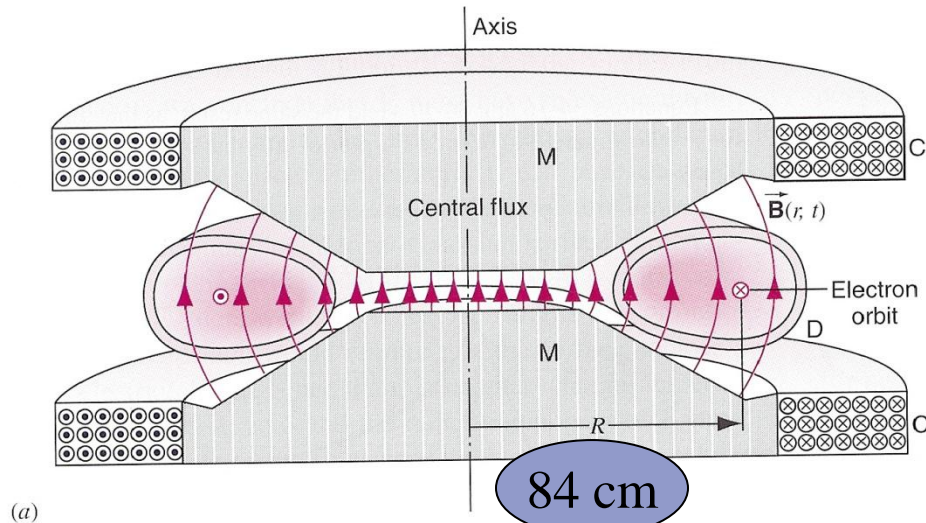
## Magnetické pole

- udržuje elektron na kruhové dráze
- proměnné v čase indukuje elektrické pole, které elektron urychluje



**FIGURE 34-18.** (a) Cross section of a betatron, showing the orbit of the accelerating electrons and a “snapshot” of the magnetic field at a certain time during the cycle. The magnetic field is produced by the coils C and shaped by the magnetic pole pieces M. Electrons circulate within the evacuated, doughnut-shaped ceramic tube D. Electrons orbit perpendicular to the plane of the figure, entering at right and leaving at left. (b) The variation with time of the betatron magnetic field during one cycle.

# betatron



**FIGURE 34-18.** (a) Cross section of a betatron, showing the orbit of the accelerating electrons and a “snapshot” of the magnetic field at a certain time during the cycle. The magnetic field is produced by the coils C and shaped by the magnetic pole pieces M. Electrons circulate within the evacuated, doughnut-shaped ceramic tube D. Electrons orbit perpendicular to the plane of the figure, entering at right and leaving at left. (b) The variation with time of the betatron magnetic field during one cycle.

indukované napětí po jednom oběhu

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{(0,8)(\pi)(0,84)^2 \text{ Wb}}{4,2 \cdot 10^{-3} \text{ s}} = 430 \text{ V}$$

výsledná kinetická energie elektronu

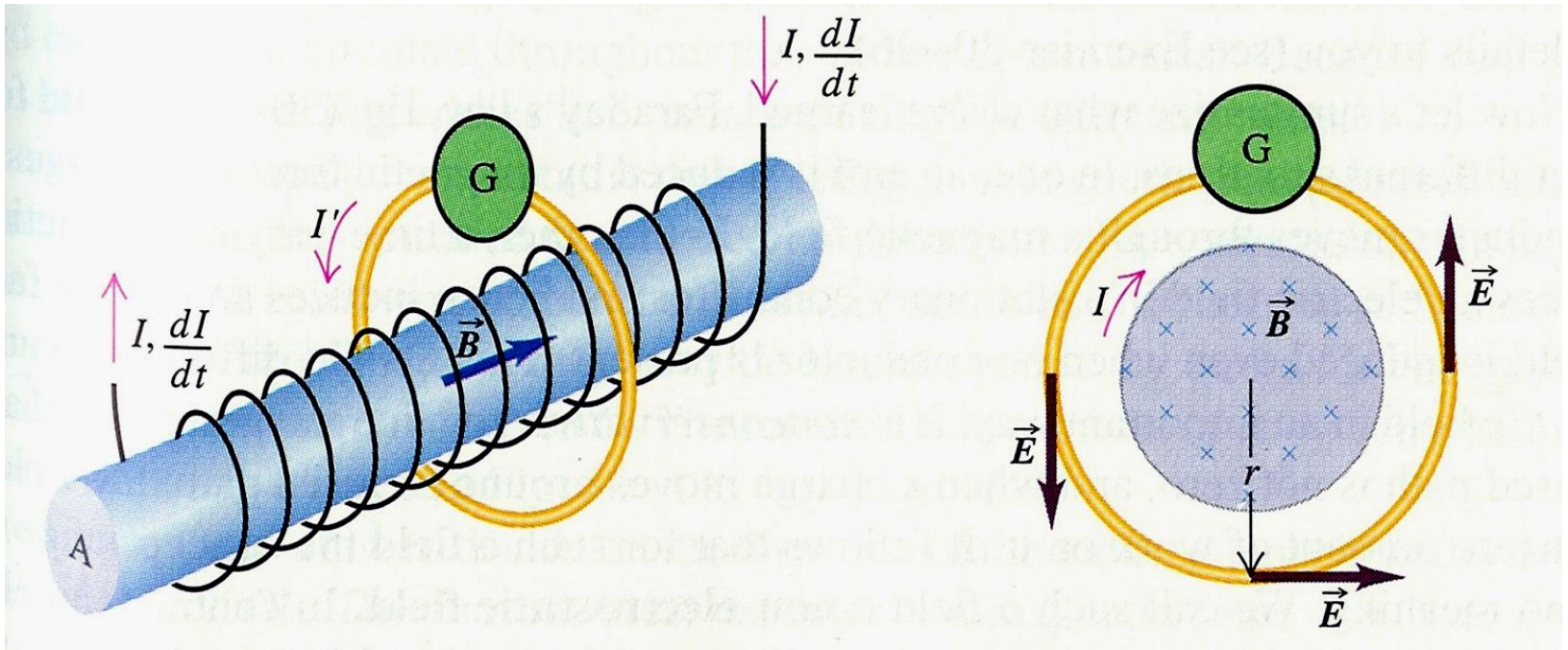
$$100 \text{ MeV} = (430 \text{ eV}) \cdot (230\,000 \text{ oběhů})$$

průměrná rychlost elektronu

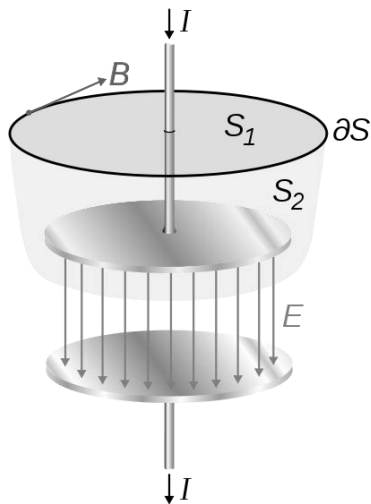
$$\bar{v} = \frac{1200 \text{ km}}{4,2 \text{ ms}} = 2,86 \cdot 10^8 \text{ m/s}$$

# indukce vně magnetického pole

$$\oint_C \vec{E} \cdot d\vec{s} = - \frac{d}{dt} \iint_S \vec{B} \cdot d\vec{S}$$

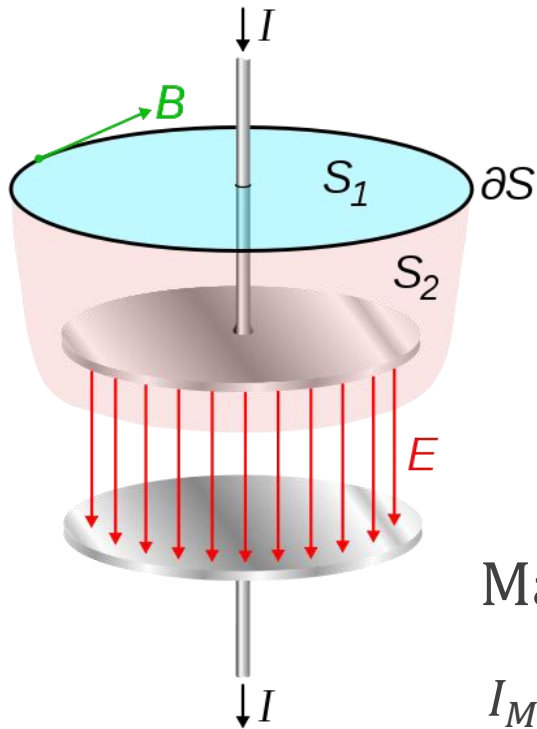


# magnetoelektrická indukce a Maxwellovy rovnice





# Ampérův-Maxwellův zákon



Ampérův zákon:

$$\oint_{\partial S} \vec{B} \cdot d\vec{s} = \mu_0 I = \mu_0 \iint_{S_1} \vec{J} \cdot d\vec{S}$$

$$\iint_{S_2} \vec{J} \cdot d\vec{S} = 0$$

Maxwellův (posuvný) proud:

$$I_M = I = \frac{dQ}{dt} = \frac{d}{dt} (\epsilon_0 S E) = \epsilon_0 \frac{d\Phi_E}{dt} = \epsilon_0 \frac{d}{dt} \iint \vec{E} \cdot d\vec{S}$$

Ampérův-Maxwellův zákon:

$$\oint_{\partial S} \vec{B} \cdot d\vec{s} = \mu_0 \iint_S \left( \vec{J} + \epsilon_0 \frac{d\vec{E}}{dt} \right) \cdot d\vec{S} = \mu_0 I + \mu_0 \epsilon_0 \frac{d}{dt} \iint_S \vec{E} \cdot d\vec{S}$$

$\vec{J}_M$

$c^{-2}$

$I_M$

# Maxwellovy rovnice

$$\oiint_S \vec{E} \cdot d\vec{S} = \frac{Q}{\epsilon_0} \quad \text{Gaussův zákon}$$

---

$$\oint_{\partial S} \vec{B} \cdot d\vec{s} = \mu_0 I + \mu_0 \epsilon_0 \frac{d}{dt} \iint_S \vec{E} \cdot d\vec{S}$$

Ampérův-Maxwellův zákon

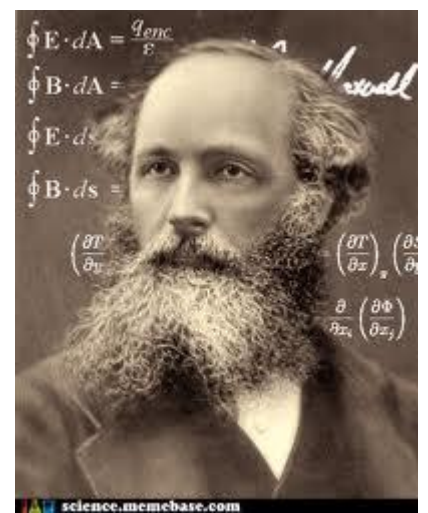
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$$\oiint_S \vec{B} \cdot d\vec{S} = 0 \quad \text{Gaussův zákon pro magnetické pole}$$

---

$$\oint_{\partial S} \vec{E} \cdot d\vec{s} = - \frac{d}{dt} \iint_S \vec{B} \cdot d\vec{S}$$

Faradayův zákon

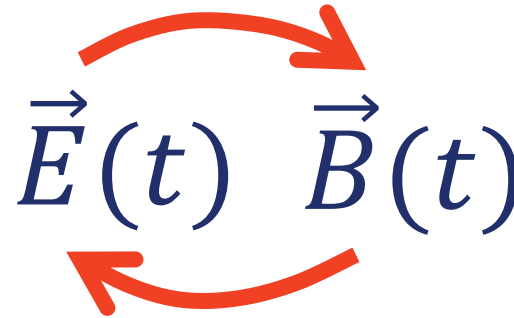


James Clerk  
Maxwell  
1831 - 1879

# kvazistacionární aproximace

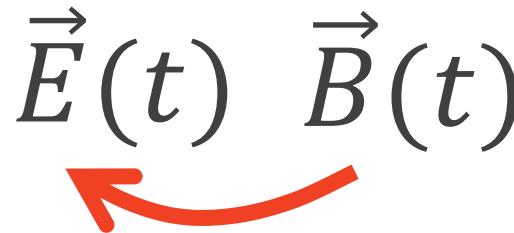
$$\oint_{\partial S} \vec{E} \cdot d\vec{s} = -\frac{d}{dt} \iint_S \vec{B} \cdot d\vec{S}$$
$$\oint_{\partial S} \vec{B} \cdot d\vec{s} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d}{dt} \iint_S \vec{E} \cdot d\vec{S}$$

(elektromagnetické pole)



$$\oint_{\partial S} \vec{E} \cdot d\vec{s} = -\frac{d}{dt} \iint_S \vec{B} \cdot d\vec{S}$$
~~$$\oint_{\partial S} \vec{B} \cdot d\vec{s} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d}{dt} \iint_S \vec{E} \cdot d\vec{S}$$~~

(kvazistacionární pole)



podmínka kvazistacionarity:

rozměr obvodu  $\longrightarrow$   $d \ll cT$   $\longleftarrow$  perioda změn polí