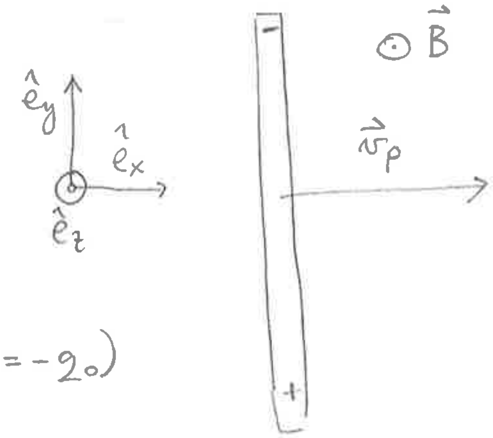
(10) "Indukcija" (navidezna indukcija) – Lorentzova sila (Hallov pojav)

Primer: premikanje vodnika po statičnem zunanjem $\vec{B}$ (gugalnica)



- $\vec{B} = B\hat{e}_z$; $B > 0$
- $\vec{v}_p = v_p \hat{e}_x$; $v_p > 0$
- l = dolžina prečke
- e^-: prosti nosilci $(q = -q_0)$

$$\vec{F}_{mag} = q\vec{v} \times \vec{B}$$
$$= -q_0 \vec{v}_p \times \vec{B}$$
$$= -q_0 v_p B(\hat{e}_x \times \hat{e}_z)$$
$$= q_0 v_p B \hat{e}_y \quad ; \quad \hat{e}_x \times \hat{e}_z = -\hat{e}_y$$

$\hat{e}_y = -\hat{e}_y$

Steče kratkotrajen tok, presežek negativnih nabojev na zgornjem delu prečke $(y \to \frac{l}{2})$, presežek negativnega naboja na spodnjem delu prečke $(y \to -\frac{l}{2})$ ⇒ ustvari se električno polje

- $\vec{E} = E\hat{e}_y$ ⇒ $\vec{E}$(palica), $\vec{v}_p$, $\vec{B}$: paroma pravokotni vektorji

⇒ na proste nosilce naboja deluje tudi električna sila

$$\vec{F}_{el} = q\vec{E}$$
$$= -q_0 E\hat{e}_y$$
$$= q_0 E(-\hat{e}_y)$$

⇒ V stacionarnih razmerah, ko toka ni več, ravnovesje obeh sil:

$$\vec{F}_{mag} + \vec{F}_{el} = 0$$

$$q_0 (v_p B - E)\hat{e}_y = 0$$

$$\Rightarrow \boxed{E = v_p B} \quad (= \text{konst.})$$

$$\Rightarrow \boxed{\vec{E} = v_p B \hat{e}_y}$$

Napetost med koncema prečke:

$$\vec{r}(t_1) = \begin{bmatrix} 0 \\ -\frac{\ell}{2} \\ 0 \end{bmatrix}, \quad \vec{r}(t_2) = \begin{bmatrix} 0 \\ \frac{\ell}{2} \\ 0 \end{bmatrix}$$ (v sistemu, v katerem prečka miruje)

C: krivulja z začetkom v $\vec{r}(t_1)$ in koncem v $\vec{r}(t_2)$

$$\boxed{U(\vec{r}_1 \to \vec{r}_2) =} - \int_C \vec{E} \cdot d\vec{s} = -\int_{t_1}^{t_2} \vec{E} \cdot \dot{\vec{r}}\, dt = -\int_{t_1}^{t_2} E \dot{y}\, dt = -E \int_{t_1}^{t_2} \dot{y}\, dt = -E\, y\Big|_{t_1}^{t_2} = -E\ell$$

$$\dot{\vec{r}} = \dot{x}\hat{e}_x + \dot{y}\hat{e}_y + \dot{z}\hat{e}_z$$

$$\boxed{= -v_p B \ell}$$

Če se prečka premika v drugo nasprotno smer:

- $\vec{v}_p = v_p(-\hat{e}_x)\,;\ v_p > 0$

⋮

- $\boxed{U(\vec{r}_1 \to \vec{r}_2) = +v_p B \ell}$

Napetost lahko izrazimo z mešanim produktom:

$$\boxed{U(\vec{r}_1 \to \vec{r}_2) = \vec{v}_p \cdot (\vec{B} \times \vec{\ell})}\,; \quad \boxed{\vec{\ell} = \ell \hat{e}_\ell\,;\ \hat{e}_\ell = \frac{\vec{r}_2 - \vec{r}_1}{|\vec{r}_2 - \vec{r}_1|}}$$ (mešani produkt)

- v našem primeru: $\vec{r}_2 - \vec{r}_1 = \ell \hat{e}_y \Rightarrow \hat{e}_\ell = \hat{e}_y$

$$\Rightarrow U(\vec{r}_1 \to \vec{r}_2) = v_p \hat{e}_x \cdot (B\ell\, \hat{e}_z \times \hat{e}_y)$$

$$= v_p B \ell\, \hat{e}_x \cdot (\hat{e}_z \times \hat{e}_y)$$

$$= v_p B \ell\, \hat{e}_x \cdot (-\hat{e}_x)$$

$$= -v_p B \ell \quad \checkmark$$

$$\Rightarrow U(\vec r_1 \to \vec r_2) = v_p(-\hat e_x)\cdot(\vec B \times \vec l)$$
$$= -v_p B l\, \hat e_x \cdot (\hat e_z \times \hat e_y)$$
$$= -v_p B l\, \hat e_x \cdot (-\hat e_x)$$
$$= v_p B l \quad \checkmark$$

Enačba

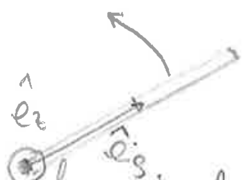
$$\boxed{U(\vec r_1 \to \vec r_2) = \vec v_p \cdot (\vec B \times \vec l)}$$

velja tudi, ko $\vec v_p, \vec B, \vec l$ niso paroma pravokotni.

Posplošitev enačbe, ko $\vec B$ ni konstantno in/ali prečka (vodnik) ni ravna in/ali $\vec v_p$ ni konstanta:

$$\boxed{U(\vec r_1 \to \vec r_2) = \int_C \vec v_p \cdot (\vec B \times d\vec l)}$$, kjer integriramo vzdolž vodnika (prečke)

Primer: palico v zunanjem $\vec B$ vrtimo okrog enega izmed krajišč;



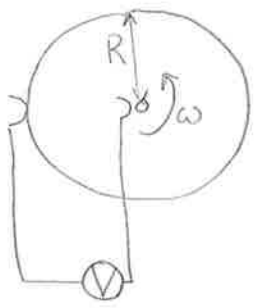
- $\vec B = B\hat e_z$, $B > 0$
- ω : kotna hitrost ($\dot\phi$)
- $\vec r = r\hat e_\varrho$ (cilindrični koordinatni sistem) ; $r = $ konst.
- $\vec v_p = \dot r \hat e_\varrho + r\dot{\hat e}_\varrho = r\dot\phi\, \hat e_\phi = r\omega\, \hat e_\phi$
- $d\vec l = \hat e_\varrho \cdot dr$

$$\Rightarrow dU_i = \vec v_p \cdot (\vec B \times d\vec l)$$
$$= \omega r \hat e_\phi \cdot (B\, dr\, \hat e_z \times \hat e_\varrho)$$
$$= \omega B r\, dr\, \hat e_\phi \cdot (\underbrace{\hat e_z \times \hat e_\varrho}_{\hat e_\phi})$$
$$= \omega B r\, dr$$

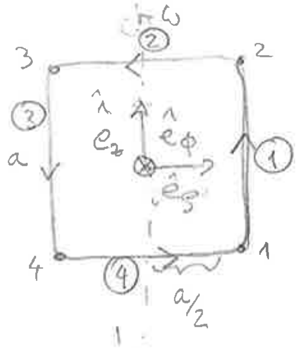
$$\Rightarrow \boxed{U_i = \int_0^R \omega B r\,dr = \frac{1}{2}\omega B R^2}$$

Primer: disk, ki se vrti v zunanjem $\vec{B}$

$\odot\,\vec{B}$

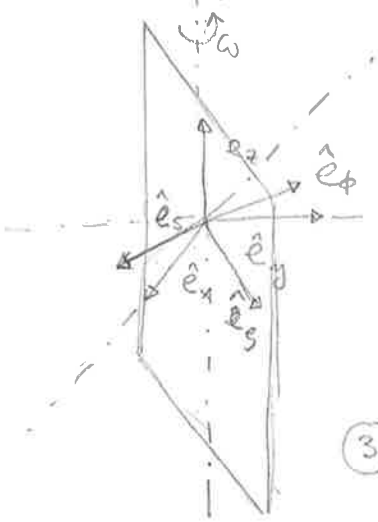


Primer: kvadratna zanka se vrti v zunanjem $\vec{B}$



$\vec{B} = B\,\hat{e}_y$; $B>0$

$\vec{S} = S\,\hat{e}_s = a^2(-\hat{e}_\phi)$ $\quad(\hat{e}_s = -\hat{e}_\phi)$



(1) $\vec{v}_p = \frac{a}{2}\omega\,\hat{e}_\phi = \frac{a}{2}\omega\left(-\sin\phi\, e_x + \cos\phi\,\hat{e}_y\right)$

$\vec{l} = a\,\hat{e}_z$

$$\Rightarrow \vec{B}\times\vec{l} = aB\,(\overbrace{\hat{e}_y\times\hat{e}_z}^{\hat{e}_x}) = aB\,\hat{e}_x$$

$$\Rightarrow \boxed{U_1 = \vec{v}_p\cdot(\vec{B}\times\vec{l}) = \frac{a^2}{2}B\omega\left[(-\sin\phi\, e_x + \cos\phi\,\hat{e}_y)\cdot\hat{e}_x\right] = -\frac{a^2}{2}B\omega\sin\phi}$$

(3) $\vec{v}_p = -\frac{a}{2}\omega\,\hat{e}_\phi$

$\vec{l} = -a\,\hat{e}_z$

$$\Rightarrow \boxed{U_3 = U_1 = -\frac{a^2}{2}B\omega\sin\phi}$$

(2) $d\vec{l} = dr(-\hat{e}_s) = -dr(\cos\phi\, e_x + \sin\phi\,\hat{e}_y)$, $\vec{v}_p = r\omega(-\sin\phi\,\hat{e}_x + \cos\phi\,\hat{e}_y)$

$$\Rightarrow \vec{B}\times d\vec{l} = -B\,dr\left[\hat{e}_y\times(\cos\phi\,\hat{e}_x + \sin\phi\,\hat{e}_y)\right] = -B\,dr\left[\cos\phi\,(\overbrace{\hat{e}_y\times\hat{e}_x}^{-\hat{e}_z}) + \sin\phi\,(\overbrace{\hat{e}_y\times\hat{e}_y}^{0})\right]$$

$$= B\cos\phi\,dr\,\hat{e}_z$$

$\Rightarrow \; dU_2 = \vec{v}_p \cdot (\vec{B} \times d\vec{l})$

$= B\cos\phi\,\omega r\,dr\,(-\sin\phi\,\hat{e}_x + \cos\phi\,\hat{e}_y) \cdot \hat{e}_z$

$= 0$

$\Rightarrow \boxed{U_2 = 0}$

④ $U_4 = 0$

$\Rightarrow \boxed{U = U_1 + U_2 + U_3 + U_4 = -a^2 B\omega \sin\phi}$; generator izmenične napetosti !

$\Phi_B = \vec{S} \cdot \vec{B} = SB\,\hat{e}_S \cdot \hat{e}_B$

$= a^2 B\,(-\hat{e}_\phi) \cdot \hat{e}_y$

$= a^2 B\,(\sin\phi\,\hat{e}_x - \cos\phi\,\hat{e}_y) \cdot \hat{e}_y$

$= -a^2 B \cos\phi$

$\Rightarrow \dfrac{d\Phi_B}{dt} = a^2 B\omega \sin\phi \qquad (\omega = \dot{\phi})$

$\Rightarrow \boxed{U = -\dfrac{d\Phi_B}{dt}}$ ...... (1)

- $\Phi_B = \Phi_B(t)$ zaradi $\vec{S} = \vec{S}(t)$ $\left(\vec{S} = a^2\hat{e}_S = a^2(-\hat{e}_\phi) = a^2(\sin\phi\,\hat{e}_x - \cos\phi\,\hat{e}_y);\ \phi = \phi(t)\right)$
- Enačba (1) odgovre npr. pri vrtenju diska v zunanjem $\vec{B}$ (ni splošna!)

Primerjaj z :

$$\oint_{\partial S} \vec{E} \cdot d\vec{s} = -U_i = -\int_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S}$$

Če $\vec{S}$ in smer $\vec{B}$ konstantna ;

$$\Rightarrow \int_S \frac{\partial \vec{B}}{\partial t} \cdot d\vec{S} = \frac{\partial}{\partial t} \int_S \vec{B} \cdot d\vec{S} = \frac{\partial}{\partial t} \Phi_B$$

$\Rightarrow \boxed{U_i = \dfrac{\partial \Phi_B}{\partial t}}$ ...... (2)

- $\Phi_B = \Phi_B(t)$ zaradi $B = B(t)$
- Enačba (2) velja splošno (zelo o električni napetosti)

(11) EM valovanje

Maxwellove enačbe v diferencialni obliki:

$$\boxed{\begin{aligned} &\nabla\cdot\vec{B} = 0 \\ &\nabla\cdot\vec{E} = \rho/\varepsilon_0 \quad (= \rho/\varepsilon\varepsilon_0) \\ &\nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \\ &\nabla\times\vec{B} = \mu_0\vec{j} + \frac{1}{c_0^2}\frac{\partial\vec{E}}{\partial t} \quad \left(= \mu\mu_0\vec{j} + \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}\right) \end{aligned}}$$

pri čemer

$$\boxed{\begin{aligned} &c_0 \equiv \frac{1}{\sqrt{\mu_0\varepsilon_0}} = \text{konst.} \\ &c = \frac{c_0}{\sqrt{\mu\varepsilon}} \overset{\mu=1}{\simeq} \frac{c_0}{\sqrt{\varepsilon}} = \frac{c_0}{n} \end{aligned}} \; ; \; n = \sqrt{\varepsilon} \geq 1 \quad (\Rightarrow c \leq c_0)$$

$\rho = 0, \vec{j} = 0$:

$$\boxed{\begin{aligned} &\text{M1:} \quad \nabla\cdot\vec{B} = 0 \\ &\text{M2:} \quad \nabla\cdot\vec{E} = 0 \\ &\text{M3:} \quad \nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \\ &\text{M4:} \quad \nabla\times\vec{B} = \frac{1}{c_0^2}\frac{\partial\vec{E}}{\partial t} \quad \left(= \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}\right) \end{aligned}}$$

$\downarrow$ v vakuumu $\qquad \downarrow$ v snovi

Mat: • $\vec{E}$ poljubno vektorsko polje (lahko jakost el. polja, lahko $\vec{B}$, ali pa katerokoli drugo vektorsko polje)

$$\boxed{\nabla\times(\nabla\times\vec{E}) = \nabla(\nabla\cdot\vec{E}) - \nabla^2\vec{E}},$$

pri čemer:

$$\left.\begin{aligned} \nabla^2 &= \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \\ \vec{E} &= \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} \end{aligned}\right\} \Rightarrow \nabla^2\vec{E} = \begin{bmatrix} \nabla^2 E_x \\ \nabla^2 E_y \\ \nabla^2 E_z \end{bmatrix}$$

M3: $\nabla\times(\nabla\times\vec{E}) = \nabla\times\left(-\frac{\partial\vec{B}}{\partial t}\right)$ ($\vec{E}$ jakost el. polja, $\vec{B}$ gostota mag. polja)

$$\underbrace{\nabla(\nabla\cdot\vec{E})}_{\overset{(M2)}{=}\,0} - \nabla^2\vec{E} = -\frac{\partial}{\partial t}\underbrace{(\nabla\times\vec{B})}_{\overset{(M4)}{=}\,\frac{1}{c_0^2}\frac{\partial\vec{E}}{\partial t}}$$

$$\Rightarrow -\nabla^2\vec{E} = -\frac{1}{c_0^2}\frac{\partial^2\vec{E}}{\partial t^2}$$

$$\Rightarrow \boxed{\nabla^2\vec{E} = \frac{1}{c_0^2}\frac{\partial^2\vec{E}}{\partial t^2}}$$ Valovna enačba za $\vec{E}$ v praznem prostoru (v snovi: $c_0^2 \to c^2$)

Podobno:

M4: $\nabla\times(\nabla\times\vec{B}) = \frac{1}{c_0^2}\nabla\times\left(\frac{\partial\vec{E}}{\partial t}\right)$

$$\underbrace{\nabla(\nabla\cdot\vec{B})}_{\overset{(M1)}{=}\,0} - \nabla^2\vec{B} = \frac{1}{c_0^2}\frac{\partial}{\partial t}\underbrace{(\nabla\times\vec{E})}_{\overset{(M3)}{=}\,-\frac{\partial\vec{B}}{\partial t}}$$

$$\Rightarrow -\nabla^2 \vec{B} = -\frac{1}{c_0^2}\frac{\partial^2 \vec{B}}{\partial t^2}$$

$$\Rightarrow \boxed{\nabla^2 \vec{B} = \frac{1}{c_0^2}\frac{\partial^2 \vec{B}}{\partial t^2}}$$ Valovna enačba za $\vec{B}$ v praznem prostoru (v snovi: $c_0^2 \to c^2$)

Komentarji:

- EM valovanje (motnja v $\vec{E}$ in $\vec{B}$) se lahko širi skozi prazen prostor
- Hitrost c_0 EM valovanja v praznem prostoru: $c_0 = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = $ konst. (enaka v vseh inercialnih koordinatnih sistemih (!?!)); Michelson - Morley
- EM valovanje se lahko širi tudi skozi snov: $c_0 \to c = \frac{c_0}{n} \leq c_0$

Primer rešitve:

$$\vec{E} = \begin{bmatrix} E_{0,x} \sin(kx - \omega t + \delta_{Ex}) \\ E_{0,y} \sin(kx - \omega t) \\ E_{0,z} \sin(kx - \omega t + \delta_{Ez}) \end{bmatrix} ; \vec{B} = \begin{bmatrix} B_{0,x} \sin(kx - \omega t + \delta_{Bx}) \\ B_{0,y} \sin(kx - \omega t + \delta_{By}) \\ B_{0,z} \sin(kx - \omega t + \delta_{Bz}) \end{bmatrix} ; \vec{c}_0 = c_0 \hat{e}_x$$

Res rešitev: $$\left.\begin{aligned} \nabla^2 \vec{E} &= -k^2 \vec{E} \\ \frac{\partial^2 \vec{E}}{\partial t^2} &= -\omega^2 \vec{E} \end{aligned}\right\} \Rightarrow -k^2 \vec{E} = -\frac{\omega^2}{c_0^2}\vec{E} \quad \left(k = \frac{\omega}{c}\right) \checkmark$$

Podobno za $\vec{B}$.

Dodatni pogoji

- M2: $\nabla \cdot \vec{E} = \frac{\partial}{\partial x} E_x = k E_{0,x} \cos(kx - \omega t + \delta_{Ex}) = 0 \quad \forall x, t$

$$\left.\begin{aligned} &\Rightarrow E_{0,x} = 0 \quad (\vec{E} \perp \vec{c}_0); \\ &\text{M1: } \Rightarrow B_{0,x} = 0 \quad (\vec{B} \perp \vec{c}_0) \end{aligned}\right\} \text{EM valovanje transverzalno}$$

$$\Rightarrow \vec{E} = \begin{bmatrix} 0 \\ E_{0,y} \sin(kx-\omega t) \\ E_{0,z} \sin(kx-\omega t+\delta_{Ez}) \end{bmatrix}, \quad \vec{B} = \begin{bmatrix} 0 \\ B_{0,y} \sin(kx-\omega t+\delta_{By}) \\ B_{0,z} \sin(kx-\omega t+\delta_{Bz}) \end{bmatrix}$$

M4: $\nabla \times \vec{B} = \frac{1}{c_0^2} \frac{\partial \vec{E}}{\partial t}$

$$\frac{1}{c_0^2}\frac{\partial \vec{E}}{\partial t} = \begin{bmatrix} 0 \\ -\frac{\omega}{c_0^2} E_{0,y} \cos(kx-\omega t) \\ -\frac{\omega}{c_0^2} E_{0,z} \cos(kx-\omega t+\delta_{Ez}) \end{bmatrix}$$

$$\nabla \times B = \begin{bmatrix} \frac{\partial}{\partial y} B_z - \frac{\partial}{\partial z} B_y \\ \frac{\partial}{\partial z} B_x - \frac{\partial}{\partial x} B_z \\ \frac{\partial}{\partial x} B_y - \frac{\partial}{\partial y} B_z \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{\partial}{\partial x} B_z \\ \frac{\partial}{\partial x} B_y \end{bmatrix} = \begin{bmatrix} 0 \\ -k B_{0,z} \cos(kx-\omega t+\delta_{Bz}) \\ k B_{0,y} \cos(kx-\omega t+\delta_{By}) \end{bmatrix}$$

$$= \begin{bmatrix} 0 \\ -\frac{\omega}{c_0} B_{0,z}\left[\cos(kx-\omega t)\cos\delta_{Bz} - \sin(kx-\omega t)\sin\delta_{Bz}\right] \\ \frac{\omega}{c_0} B_{0,y}\left[\cos(kx-\omega t+\delta_{Ez})\cos(\delta_{By}-\delta_{Ez}) - \sin(kx-\omega t+\delta_{Ez})\sin(\delta_{By}-\delta_{Ez})\right] \end{bmatrix}$$

$$\Rightarrow \boxed{\begin{aligned} &\frac{1}{c_0} E_{0,y}\cos(kx-\omega t) = B_{0,z}\left[\cos(kx-\omega t)\cos\delta_{Bz} - \sin(kx-\omega t)\sin\delta_{Bz}\right] \quad \text{... (1)} \\ &\frac{1}{c_0} E_{0,z}\cos(kx-\omega t+\delta_{Ez}) = -B_{0,y}\left[\cos(kx-\omega t+\delta_{Ez})\cos(\delta_{By}-\delta_{Ez}) - \sin(kx-\omega t+\delta_{Ez})\sin(\delta_{By}-\delta_{Ez})\right] \quad \text{... (2)} \end{aligned}}$$

$\underline{\underline{\forall x,t}}$

(1) $\underline{kx-\omega t = \frac{\pi}{2}}$: $-B_{0,z}\sin\delta_{Bz} = 0 \Rightarrow \delta_{Bz} = 0, \pi$

$\underline{kx-\omega t = 0}$: $\frac{E_{0,y}}{c_0} = B_{0,y}\cos\delta_{B,z}$

- $\delta_{B,z} = \pi \Rightarrow B_{0,y} = -\frac{E_{0,y}}{c_0} < 0$ //
- $\boxed{\delta_{B,z} = 0} \Rightarrow \boxed{B_{0,y} = \frac{E_{0,y}}{c_0}}$ (>0 ✓)

(2) $\underline{kx-\omega t+\delta_{Ez}=\frac{\pi}{2}}$: $B_{01y}\sin(\delta_{By}-\delta_{Ez})=0 \Rightarrow \delta_{By}-\delta_{Ez}=0,\pi$

$\underline{kx-\omega t+\delta_{Ez}=0}$: $\frac{E_{01z}}{c_0} = -B_{01y}\cos(\delta_{By}-\delta_{Ez})$

- $\delta_{By}-\delta_{Ez}=0 \Rightarrow B_{01y}=-\frac{E_{01z}}{c_0}<0$ //

- $\boxed{\delta_{By}-\delta_{Ez}=\pi} \Rightarrow \boxed{B_{01y}=\frac{E_{01z}}{c_0}} >0$ ✓

$$\Downarrow$$

$$\delta_{By}=\delta_{Ez}+\pi$$

$$\Rightarrow \sin(kx-\omega t+\delta_{Bz}) = \sin(kx-\omega t+\delta_{Ez}+\pi)$$
$$= -\sin(kx-\omega t+\delta_{Ez})$$

$$\Rightarrow \vec{B} = \begin{bmatrix} 0 \\ -\frac{E_{01z}}{c_0}\sin(kx-\omega t+\delta_{Ez}) \\ \frac{E_{01y}}{c_0}\sin(kx-\omega t) \end{bmatrix}$$

- $\Rightarrow \vec{B}\cdot\vec{E}=0 \quad (\vec{B}\perp\vec{E})$

$$\Rightarrow \boxed{\vec{B}\perp\vec{E}\perp\vec{c}_0}$$

$$\Rightarrow \boxed{B^2} = \frac{E_{01z}^2}{c_0^2}\sin^2(kx-\omega t+\delta_{Ez}) + \frac{E_{01y}^2}{c_0^2}\sin^2(kx-\omega t) = \boxed{\frac{E^2}{c_0^2}}$$

$$\Rightarrow \boxed{\vec{B}\times\vec{c}_0} = \begin{bmatrix} 0 \\ c_0 B_z \\ -c_0 B_y \end{bmatrix} = \begin{bmatrix} 0 \\ E_{01y}\sin(kx-\omega t) \\ E_{01z}\sin(kx-\omega t+\delta_{Ez}) \end{bmatrix} = \boxed{\vec{E}}$$

Energijski tok EM valovanja

$$w_E = \frac{1}{2}\varepsilon_0 E^2$$

$$w_B = \frac{1}{2}\frac{B^2}{\mu_0} = \frac{1}{2\mu_0}\frac{E^2}{c_0^2} = \frac{1}{2}\frac{\varepsilon_0\mu_0}{\mu_0}E^2 = \frac{1}{2}\varepsilon_0 E^2 = w_E$$

$$\Rightarrow w = w_E + w_B = \varepsilon_0 E^2$$

$$\Rightarrow \boxed{\vec{j}_{EM} = w\vec{c}_0} = \varepsilon_0 E^2 c_0 \hat{e}_x = \varepsilon_0 c_0^2 \frac{E^2}{c_0}\hat{e}_x = \frac{\varepsilon_0}{\varepsilon_0\mu_0}\frac{E^2}{c_0}\hat{e}_x = \boxed{\frac{1}{\mu_0}\frac{E^2}{c_0}\hat{e}_x}$$

Hkrati velja:

$$\vec{E}\times\vec{B} = \begin{bmatrix} E_y B_z - E_z B_y \\ E_z B_x - E_x B_z \\ E_x B_y - E_y B_x \end{bmatrix} = \begin{bmatrix} E_y B_z - E_z B_y \\ 0 \\ 0 \end{bmatrix}$$

$$= \left[\frac{E_{0,y}^2}{c_0}\sin^2(kx-\omega t) + \frac{E_{0,z}^2}{c_0}\sin^2(kx-\omega t+\delta_{E,z})\right]\hat{e}_x$$

$$= \frac{E^2}{c_0}\hat{e}_x$$

$$\Rightarrow \boxed{\vec{\wp} \equiv \vec{E}\times\frac{\vec{B}}{\mu_0} = \frac{1}{\mu_0}\frac{E^2}{c_0}\hat{e}_x = \vec{j}_{EM}}$$ (Poyntingov vektor)