总结一个.

一、电荷：$\rho=\rho_f+\rho_p=\rho_f-\nabla\cdot\vec{P}$

电流：$\vec{J}=\vec{J}_f+\vec{J}_M+\vec{J}_P=\vec{J}_f+\nabla\times\vec{M}+\frac{\partial\vec{P}}{\partial t}$，$\vec{J}_f=\vec{J}_c+\vec{J}_e$

Maxwell：

$$\nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t}$$
$$\nabla\times\vec{H}=\vec{J}_f+\frac{\partial\vec{D}}{\partial t}$$
$$\nabla\cdot\vec{D}=\rho_f$$
$$\nabla\cdot\vec{B}=0$$

边界：

$$\hat{n}\times(\vec{E}_2-\vec{E}_1)=0$$
$$\hat{n}\times(\vec{H}_2-\vec{H}_1)=\vec{J}_s$$
$$\hat{n}\cdot(\vec{D}_2-\vec{D}_1)=\rho_s$$
$$\hat{n}\cdot(\vec{B}_2-\vec{B}_1)=0$$

线性、各向同性、非色散：$\vec{B}=\mu\vec{H}$，$\vec{D}=\varepsilon\vec{E}$，$\vec{J}_c=\sigma\vec{E}$.

…色散：$\vec{D}(t)=\varepsilon_0\int_{-\infty}^{t}\varepsilon_r(t-t')\vec{E}(t')dt'$，$\vec{B}(t)=\mu_0\int_{-\infty}^{t}\mu_r(t-t')\vec{H}(t')dt'$，因果性.

Poynting：$-\nabla\cdot\vec{S}=\frac{\partial w_e}{\partial t}+\frac{\partial w_m}{\partial t}+p_d+p_s$.　　$\vec{S}=\vec{E}\times\vec{H}$.

$w_e=\frac{1}{2}\vec{E}\cdot\vec{D}$，$w_m=\frac{1}{2}\vec{B}\cdot\vec{H}$

$p_d=\sigma\vec{E}^2$，$p_s=\vec{J}_e\cdot\vec{E}$.

时谐场/源下的Maxwell：

$$\nabla\times\vec{E}=i\omega\vec{B}$$
$$\nabla\times\vec{H}=\vec{J}_f-i\omega\vec{D}$$
$$\nabla\cdot\vec{D}=\rho_f$$
$$\nabla\cdot\vec{B}=0.$$

线性、各向同性、色散/非色散：$\vec{D}(\omega)=\varepsilon(\omega)\vec{E}(\omega)$，$\vec{B}(\omega)=\mu(\omega)\vec{H}(\omega)$.

Poynting：$-\nabla\cdot\tilde{S}=2i\omega(\tilde{w}_e-\tilde{w}_m)+\frac{1}{2}\sigma\vec{E}\cdot\vec{E}^*+\frac{1}{2}\vec{J}_e^*\cdot\vec{E}$　　$\tilde{S}=\frac{1}{2}\vec{E}\times\vec{H}^*$.

$\tilde{w}_e=\frac{1}{4}\vec{E}\cdot\vec{D}^*$，$\tilde{w}_m=\frac{1}{4}\vec{B}\cdot\vec{H}^*$

$-\nabla\cdot\langle\vec{S}\rangle=\frac{1}{2}\omega\varepsilon''|\vec{E}|^2+\frac{1}{2}\omega\mu''|\vec{H}|^2+\frac{1}{2}\sigma|\vec{E}|^2+Re\left\{\frac{\vec{J}_e^*\cdot\vec{E}}{2}\right\}$　　$\langle\vec{S}\rangle=\frac{1}{2}Re\{\vec{E}\times\vec{H}^*\}$.

Maxwell 解的唯一性

$\begin{cases} \text{区域内 } t=0 \text{ 时 } \vec{E}、\vec{H} \text{ 已知} \\ \text{边界上 } t>0 \text{ 时 } \vec{E}_t|_s\ \vec{H}_t|_s \text{ 已知} \end{cases}$ 区域内 $\vec{E}(t)\ \vec{H}(t)$ 唯一确定.

$\Rightarrow$

$$\begin{cases} \nabla\times\vec{E} = -\frac{\partial\vec{B}}{\partial t} \\ \nabla\times\vec{H} = \vec{J}_e + \sigma\vec{E} + \frac{\partial\vec{D}}{\partial t} \\ \nabla\cdot\vec{D} = \rho \\ \nabla\cdot\vec{B} = 0 \end{cases}$$

假设 $(\vec{E}_1, \vec{H}_1)$ $(\vec{E}_2, \vec{H}_2)$ 是两组解

令 $\vec{E} = \vec{E}_2 - \vec{E}_1$

$\vec{H} = \vec{H}_2 - \vec{H}_1$

得到

$$-\oint(\vec{E}\times\vec{H})\cdot d\vec{s} = \frac{d}{dt}\int_V\left(\frac{1}{2}\varepsilon\vec{E}^2 + \frac{1}{2}\mu\vec{H}^2\right)dV + \int\sigma\vec{E}^2 dV$$

$t>0$ 时，$\vec{E}_t|_s = 0$ $\vec{H}_t|_s = 0$ $\oint(\vec{E}\times\vec{H})\cdot d\vec{s} = 0$.

$\therefore$ $\frac{d}{dt}\int_V\left(\frac{1}{2}\varepsilon\vec{E}^2 + \frac{1}{2}\mu\vec{H}^2\right)dV = -\int\sigma\vec{E}^2 dV \leq 0$.

$t=0$ 时，$\frac{1}{2}\varepsilon\vec{E}^2 + \frac{1}{2}\mu\vec{H}^2 = 0$.

$\therefore \frac{1}{2}\varepsilon\vec{E}^2 + \frac{1}{2}\mu\vec{H}^2 = 0$ $\therefore E=0, H=0$.

二、真空或介质中：

解得 $\begin{cases} \nabla^2\vec{E}+k^2\vec{E}=0 \\ \nabla\cdot\vec{E}=0 \\ \vec{B}=-\frac{i}{\omega}\nabla\times\vec{E} \end{cases}$ 　或 $\begin{cases} \nabla^2\vec{B}+k^2\vec{B}=0 \\ \nabla\cdot\vec{B}=0 \\ \vec{E}=\frac{i}{\omega\mu\varepsilon}\nabla\times\vec{B} \end{cases}$

均匀平面波解：

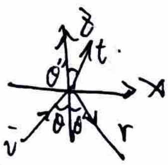
$\vec{E}=\vec{E}_0 e^{i(\vec{k}\cdot\vec{x}-\omega t)}$ 　$\vec{E}_{real}=Re\{\vec{E}\}$ 　$\vec{H}=\frac{1}{\omega\mu}\vec{k}\times\vec{E}=\frac{1}{\eta}\hat{k}\times\vec{E}$. 　$(\eta_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}\approx 120\pi\approx 377\Omega)$

$\begin{cases} \text{均匀：等振幅面……} \\ \text{平面：等相位面……} \\ \text{横波：}\vec{k}\cdot\vec{E}=0 \end{cases}$

$v_p\left(=\frac{\omega}{k}\right)=v_g\left(=\frac{d\omega}{dk}\right)=v_e\left(=\frac{\langle S\rangle}{\langle w_{em}\rangle}\right)$

$\langle w_e\rangle=\langle w_m\rangle=\frac{1}{4}\varepsilon|E_0|^2$，$\langle\vec{S}\rangle=\frac{|E_0|^2}{2\eta}\hat{k}$，$w_e=w_m=\frac{1}{2}\varepsilon E^2$，$\vec{S}=\frac{E^2}{\eta}\hat{k}$.

三、介质表面上



$\vec{k}\cdot\vec{x} = \vec{k}'\cdot\vec{x} = \vec{k}''\cdot\vec{x}$，$k_x = k_x' = k_x''$

$k_x = k\sin\theta$，$k_x' = k'\sin\theta'$，$k_x'' = k''\sin\theta''$

$k' = k = \frac{\omega}{v_1}$，$k'' = \frac{\omega}{v_2}$.

∴ $\theta = \theta'$，$\frac{\sin\theta}{\sin\theta''} = \frac{v_1}{v_2} = n_{21}$.

N波（垂直极化）

$$\begin{cases} E + E' = E'' \\ H\cos\theta - H'\cos\theta' = H''\cos\theta'' \end{cases}$$

$H = \sqrt{\frac{\varepsilon}{\mu}}E$ | 各媒质

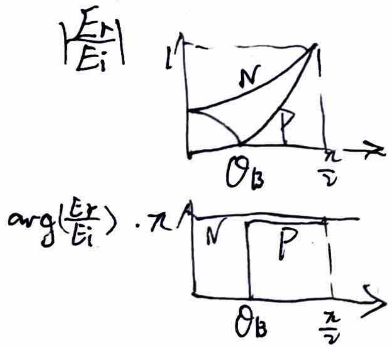
光疏→光密

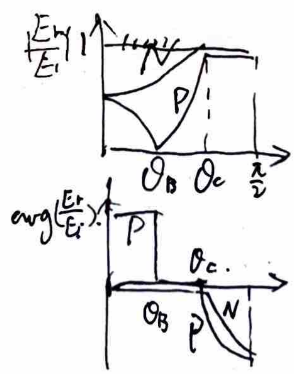
P波（平行极化）

$$\begin{cases} E\cos\theta - E'\cos\theta' = E''\cos\theta'' \\ H + H' = H'' \end{cases}$$

$H = \sqrt{\frac{\varepsilon}{\mu}}E$ | 各媒质.

光密→光疏



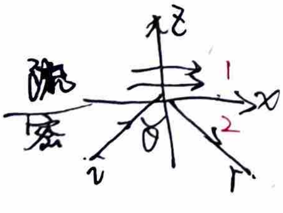


讨论：

① Brewster：$\theta_B = \mathrm{arctg}(n_2/n_1)$. ∴ P波全折射

② 半波损失：
- N波：光疏→光密.
- P波：光疏→光密 $\theta > \theta_B$，光密→光疏 $\theta < \theta_B$.

③ 全反射　$k_z'' = \sqrt{k''^2 - k_x''^2} = ik\sqrt{\sin^2\theta - n_{21}^2}$，令 $\kappa = k\sqrt{\sin^2\theta - n_{21}^2}$，则：



1) $\vec{E}'' = \vec{E}_0'' e^{i(\vec{k}''\cdot\vec{x} - \omega t)} = \vec{E}_0'' e^{-\kappa z} e^{i(k_x'' x - \omega t)}$.　非均匀平面波

$v_p'' = \frac{\omega}{k_x''} < \frac{\omega}{k''}$ ($k_x'' > k''$) ⇒ 慢波.

2) $\vec{E} + \vec{E}' = 2\vec{E}_{01}\cos(k_z z + \phi)\, e^{i(k_x x - \omega t - \phi)}$　非均匀平面波

$v_p = \frac{\omega}{k_x} > \frac{\omega}{k}$ ($k_x < k$) ⇒ 快波.

其中，$E'/E = e^{-2i\phi}$，$\phi = \begin{cases} \mathrm{arctg}\dfrac{\sqrt{\sin^2\theta_i - n_{21}^2}}{\cos\theta_i} & N \\ \mathrm{arctg}\dfrac{\sqrt{\sin^2\theta_i - n_{21}^2}}{n_{21}^2\cos\theta_i} & P \end{cases}$

∵ $k_x < k < k'' < k_x''$

∴ $v_p'' < v_2 < v_1 < v_p$

四. 导体中.

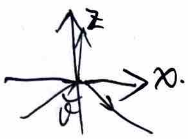
解得 $\begin{cases} \nabla^2\vec{E}+\omega^2\mu\tilde{\varepsilon}\vec{E}=0 \\ \nabla\cdot\vec{E}=0 \end{cases}$ 　　$\tilde{\varepsilon}=\varepsilon+i\frac{\sigma}{\omega}$ 　　$k^2=\omega^2\mu\tilde{\varepsilon}=(\vec{\beta}+i\vec{\alpha})^2$.

均匀平面波解:

$\vec{E}=\vec{E}_0 e^{-\vec{\alpha}\cdot\vec{x}} e^{i(\vec{\beta}\cdot\vec{x}-\omega t)}$ 　$\vec{E}_{real}=\mathrm{Re}\{\vec{E}\}$, 　$\vec{H}=\frac{1}{\omega\mu}(\vec{\beta}+i\vec{\alpha})\times\vec{E}$.

$\begin{cases} \text{均匀}: e^{-\vec{\alpha}\cdot\vec{x}} \\ \text{平面}: \vec{\beta}\cdot\vec{x}-\omega t \\ (\vec{\beta}+i\vec{\alpha})\cdot\vec{E}=0 \quad \vec{\beta}\cdot\vec{E}\neq 0. \end{cases}$

五. 良导体表面上.　　$\frac{\sigma}{\varepsilon\omega} \gg 1$.



$$k_x = k_x' = \beta_x + i\alpha_x \Rightarrow \alpha_x = 0,\ \beta_x = k_x$$

$$k^2 = \beta^2 - \alpha^2 + 2i\vec{\alpha}\cdot\vec{\beta} = \omega^2\mu\left(\varepsilon + i\frac{\sigma}{\omega}\right) \approx i\omega\mu\sigma.$$

$$\therefore \beta^2 - \alpha^2 \approx 0,\quad \vec{\alpha}\cdot\vec{\beta} = \alpha_z\beta_z = \frac{1}{2}\omega\mu\sigma = \frac{1}{2}\omega\mu\varepsilon_0\left(\frac{\sigma}{\omega\varepsilon_0}\right) \gg \frac{1}{2}k^2 > \frac{1}{2}k_x^2.$$

$$\therefore \alpha_z \approx \beta_z \approx \sqrt{\frac{\omega\mu\sigma}{2}},\quad \beta_x \ll \beta_z.\quad \delta = \frac{1}{\alpha} = \sqrt{\frac{2}{\omega\mu\sigma}}.$$

$$\therefore \begin{cases} \vec{H} = \frac{1}{\omega\mu}(\beta_z + i\alpha_z)\hat{n}\times\vec{E} \approx \sqrt{\frac{\sigma}{\omega\mu}}\, e^{i\frac{\pi}{4}}\, \hat{n}\times\vec{E}. \\ \sqrt{\frac{\mu}{\varepsilon}}\left|\frac{H}{E}\right| = \sqrt{\frac{\sigma}{\omega\varepsilon}} \gg 1 \end{cases}$$

$\vec{H}$ 滞后 $\vec{E}$ $\frac{\pi}{4}$

磁场能 ≫ 电场能.

N波. 垂直入射

$$\begin{cases} E + E' = E'' \\ H - H' = H'' \\ H = \sqrt{\frac{\varepsilon_0}{\mu_0}}E,\ H' = \sqrt{\frac{\varepsilon_0}{\mu_0}}E' \\ H'' = \sqrt{\frac{\sigma}{\omega\mu}}\, e^{i\frac{\pi}{4}}E'' \end{cases}$$

P波. 垂直入射.

$$\begin{cases} E - E' = E'' \\ H + H' = H'' \\ H = \sqrt{\frac{\varepsilon_0}{\mu_0}}E,\ H' = \sqrt{\frac{\varepsilon_0}{\mu_0}}E' \\ H'' = \sqrt{\frac{\sigma}{\omega\mu}}\, e^{i\frac{\pi}{4}}E'' \end{cases}$$

$$R = \left|\frac{E'}{E}\right|^2 \approx 1 - 2\sqrt{\frac{2\omega\varepsilon_0}{\sigma}}.$$

讨论：良导体内的电磁波.

$$\vec{E} = \vec{E}_0 e^{-\alpha z} e^{i(\beta z - \omega t)}.$$

$$\vec{H} = \sqrt{\frac{\sigma}{\omega\mu}}\, e^{i\frac{\pi}{4}}\, \hat{n}\times\vec{E}$$

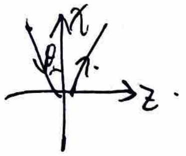
$$\vec{S} = \frac{1}{2}Re\{\vec{E}\times\vec{H}^*\} = \frac{1}{2}\sqrt{\frac{\sigma}{2\omega\mu}}E_0^2 e^{-2\alpha z}\hat{n},\quad S|_{z=0} = \frac{1}{2}\sqrt{\frac{\sigma}{2\omega\mu}}E_0^2.$$

$$P = \frac{1}{2}Re\{\vec{J}\cdot\vec{E}^*\} = \frac{1}{2}Re\{\sigma\vec{E}\cdot\vec{E}^*\} = \frac{1}{2}\sigma E_0^2 e^{-2\alpha z},\quad P_L = \int_0^\infty P\,dz = S|_{z=0}.$$

$$\vec{J}_s = \hat{n}\times\vec{H} = -\sqrt{\frac{\sigma}{\omega\mu}}\, e^{i\frac{\pi}{4}}\vec{E} = -\vec{E}_0\sqrt{\frac{\sigma}{\omega\mu}}\, e^{-\alpha z} e^{i(\beta z - \omega t)} e^{i\frac{\pi}{4}},\quad R_s = \frac{1}{\sigma\delta},\ \text{则}\ P_L = \frac{1}{2}|J_s|^2 R_s.$$

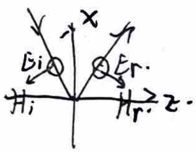
$$\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ f_x & f_y & f_z \end{vmatrix}.$$

六. 理想导体表面上. $\sigma\to\infty$ & $\delta\to 0$.



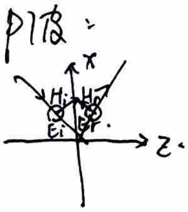
$$\hat{n}\times\vec{E}=0$$
$$\hat{n}\times\vec{H}=\vec{J}_s$$
$$\hat{n}\cdot\vec{D}=\rho_s$$
$$\hat{n}\cdot\vec{B}=0.$$

N波：



$$E_{i0}=-E_{r0}=E_0.$$
$$\vec{E}_i=E_0e^{i(k_x x+k_z z-\omega t)}\hat{e}_y$$
$$\vec{E}_r=-E_0e^{i(k_x x+k_z z-\omega t)}\hat{e}_y.$$
$$\therefore\ \vec{E}_i+\vec{E}_r=-2iE_0e^{i(k_z z-\omega t)}\sin k_x x\ \hat{e}_y.$$
$$\therefore\ \vec{H}=\frac{1}{i\omega\mu}\nabla\times\vec{E}=\frac{1}{i\omega\mu}\left(-2iE_0e^{i(k_z z-\omega t)}k_x\cos k_x x\ \hat{e}_z+2iE_0\cdot ik_z e^{i(k_z z-\omega t)}\sin k_x x\ \hat{e}_x\right)$$
$$=\frac{E_0e^{i(k_z z-\omega t)}}{i\omega\mu}\left(-2ik_x\cos k_x x\ \hat{e}_z-2k_z\sin k_x x\ \hat{e}_x\right).$$
$$=\frac{iE_0e^{i(k_z z-\omega t)}}{\omega\mu}\left(2k_z\sin k_x x\ \hat{e}_x+2ik_x\cos k_x x\ \hat{e}_z\right).$$
$$\therefore\ \rho_s=\hat{n}\cdot\varepsilon_0\vec{E}\big|_{x=0}=0.$$
$$\therefore\ \vec{J}_s=\hat{n}\times\vec{H}\big|_{x=0}=-\frac{2k_xE_0e^{i(k_z z-\omega t)}}{\omega\mu}\cos k_x x\cdot\hat{e}_y\Rightarrow-\frac{2k_xE_0}{\omega\mu}\cos(k_z z-\omega t)\hat{e}_y$$

P波：



$$\begin{cases}\vec{E}_i=(E_{ix}\hat{e}_x+E_{iz}\hat{e}_z)e^{i(k_x x+k_z z-\omega t)}\\ \vec{E}_0=(E_{0x}\hat{e}_x+E_{0z}\hat{e}_z)e^{i(k_x x+k_z z-\omega t)}\end{cases}$$

$$\because\ E_{iz}=-E_{0z}=E_z.\qquad \begin{cases}\vec{E}_i=(E_x\hat{e}_x+E_z\hat{e}_z)e^{i(k_x x+k_z z-\omega t)}\\ \vec{E}_0=(E_x\hat{e}_x-E_z\hat{e}_z)e^{i(k_x x+k_z z-\omega t)}\end{cases}.$$
$$\therefore\ E_{ix}=E_{0x}=E_x.$$
$$\therefore\ \vec{E}=\vec{E}_i+\vec{E}_0=2E_x\cos k_x x\ e^{i(k_z z-\omega t)}\hat{e}_x-2iE_z\sin k_x x\ e^{i(k_z z-\omega t)}\hat{e}_z$$
$$\therefore\ \vec{H}=\frac{1}{i\omega\mu}\nabla\times\vec{E}=\frac{2}{\omega\mu}(k_zE_x+k_xE_z)\cos k_x x\ e^{i(k_z z-\omega t)}\hat{e}_y.$$
$$\therefore\ \rho_s=2\varepsilon_0E_x\cos(k_z z-\omega t)$$
$$\vec{J}_s=\frac{2}{\omega\mu}(k_zE_x+k_xE_z)\cos(k_z z-\omega t)\hat{e}_z.$$

无源 → 有源

（科目：　　）数 学 作 业 纸

编号：　　班级：　　姓名：　　第　　页

七. 电磁辐射

$$\begin{cases}\vec{E} = -\nabla\varphi - \frac{\partial\vec{A}}{\partial t}\\ \vec{B} = \nabla\times\vec{A}\end{cases} \qquad \begin{cases}\vec{A}\to\vec{A}+\nabla\psi\\ \varphi\to\varphi-\frac{\partial\psi}{\partial t}\end{cases}$$

库仑规范：$\nabla\cdot\vec{A}=0$ （静磁、量子…）

$$\begin{cases}\nabla^2\varphi = -\frac{\rho}{\varepsilon_0}\\ \nabla^2\vec{A}-\frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2}=-\mu_0\vec{J}_t\end{cases}$$

洛伦兹规范：$\nabla\cdot\vec{A}+\frac{1}{c^2}\frac{\partial\varphi}{\partial t}=0$ （辐射、相对论）

$$\begin{cases}\nabla^2\varphi-\frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2}=-\frac{\rho}{\varepsilon_0}\\ \nabla^2\vec{A}-\frac{1}{c^2}\frac{\partial^2\vec{A}}{\partial t^2}=-\mu_0\vec{J}\end{cases} \Rightarrow \begin{cases}\varphi=\frac{1}{4\pi\varepsilon_0}\int\frac{\rho(\vec{x}',t_r)}{r}dV'\\ \vec{A}=\frac{\mu_0}{4\pi}\int\frac{\vec{J}(\vec{x}',t_r)}{r}dV'\end{cases} \Rightarrow \begin{cases}\vec{E}=\frac{1}{4\pi\varepsilon_0}\int\left(\frac{[\rho]}{r^2}\hat{r}+\frac{[\dot\rho]}{cr}\hat{r}-\frac{[\dot{\vec{J}}]}{c^2r}\right)dV'\\ \vec{B}=\frac{\mu_0}{4\pi}\int\left(\frac{[\vec{J}]}{r^2}+\frac{[\dot{\vec{J}}]}{cr}\right)\times\hat{r}\,dV'\end{cases}$$

时谐情形场

$$\vec{A}=\frac{\mu_0}{4\pi}\int\frac{\vec{J}(\vec{x}')}{r}e^{ikr}dV'$$

远处观察：$r\gg l$（系统线度，积分范围度量）

$\lambda\sim l$　　eg 半波天线　$R_r=73.2\Omega$

　　eg 天线阵　$\underbrace{|\ \ |}_{\lambda/4}$　一方向加强，一方向减弱。

$\lambda\gg l$：　$\lambda\gg r$：Near (static) zone：$e^{ikr}\sim1$　静场 $\sim\frac{1}{R^2}$

　　$\lambda\ll r$：Far (radiation) zone：　辐射场 $\sim\frac{1}{R}$

$$\vec{A}(\vec{x})\approx\frac{\mu_0}{4\pi}\int\frac{\vec{J}(\vec{x}')e^{ik(R-\hat{n}\cdot\vec{x}')}}{R-\hat{n}\cdot\vec{x}'}dV'$$

$$\approx\frac{\mu_0}{4\pi}\left(\frac{[\dot{\vec{p}}]}{R}+\frac{[\dot{\vec{m}}]\times\hat{n}}{cR}+\frac{\hat{n}\cdot[\ddot{\vec{D}}]}{6cR}+\cdots\right)$$

$\begin{cases}\text{电偶极辐射. eg 短天线}\quad R_r=197\left(\frac{l}{\lambda}\right)^2\\ \text{磁偶极辐射. eg 电流线圈.}\quad R_r\sim\left(\frac{l}{\lambda}\right)^4\ \text{更小.}\end{cases}$　$\vec{p}\to\frac{\vec{m}}{c}, \vec{E}\to c\vec{B}, \vec{B}\to-\frac{\vec{E}}{c}$

静源 → 动源

八、荷电粒子辐射

$$\varphi = \frac{1}{4\pi\varepsilon_0}\frac{q}{\left[r - \frac{\vec r\cdot\vec v}{c}\right]}$$

$$\vec A = \frac{\mu_0}{4\pi}\frac{q[\vec v]}{\left[r - \frac{\vec r\cdot\vec v}{c}\right]}.$$

$\vec E = \vec E_v + \vec E_a$　　速度场：$\propto \frac{1}{r^2}$ ⇒ 不辐射

$\vec B = \vec B_v + \vec B_a$　　加速度场 $\propto \frac{1}{r}$ ⇒ 辐射

讨论：

- $v \ll c$：电偶极辐射，$\vec p = e\vec x_0$

- $v \sim c$
  - $\vec v \parallel \vec a$：韧致　eg 软X射线、加速器
  - $\vec v \perp \vec a$：同步　eg 加速器，耗能大.