

## **E & M Qualifier**

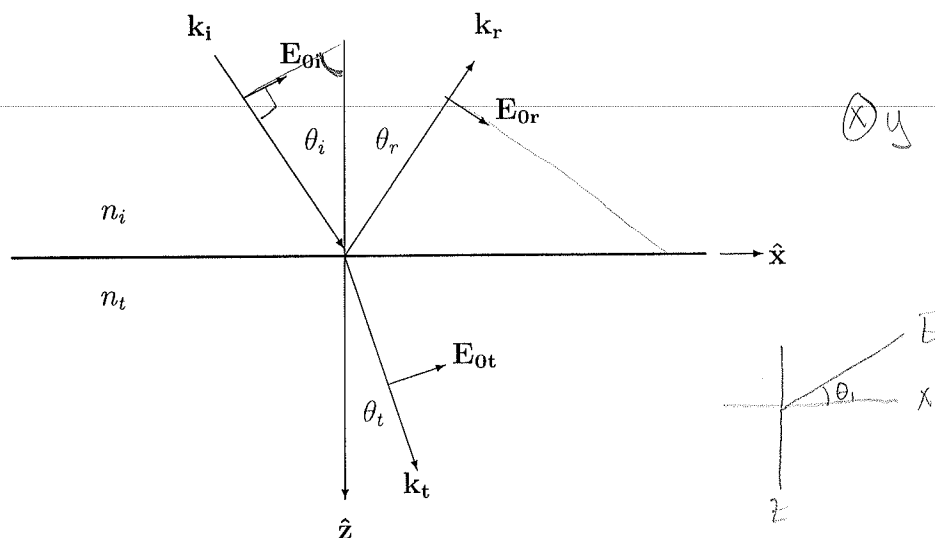
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August 15, 2013

**To insure that the your work is graded correctly you MUST:**

1. use only the blank answer paper provided,
2. write only on one side of the page,
3. put your alias (**NOT YOUR REAL NAME**) on every page,
4. put the problem # on every page,
5. start each problem by stating your units e.g., SI or Gaussian,
6. number every page starting with 1 for each problem,
7. put the total # of pages you use for that problem on every page,
8. **do not** staple your exam when done.

**Use only the reference material supplied (Schaum's Guides).**



1. A plane monochromatic electromagnetic wave of wave vector  $\mathbf{k}_i$ , amplitude  $\mathbf{E}_{0i}$ , and angular frequency  $\omega$  is incident at the planar interface of two dielectric, non-magnetic ( $\mu = \mu_0$  in SI units), non-absorbing media (i.e., have real indices of refraction  $n_i$  and  $n_t$ ). The angle of incidence is equal to  $\theta_i$ . Part of the incident wave is reflected at an angle  $\theta_r = \theta_i$  and part of it is transmitted into the second medium at a transmission angle  $\theta_t$ . Assume the electric fields of the incident, reflected, and refracted waves lie in the plane of incidence as shown in the figure. Assume coordinates are chosen so that the dielectric interface is the  $z = 0$  plane and the polarization is in the  $x$ - $z$  plane.

- (a) [2 pts] Use Maxwell's equations to derive an expression for the magnetic induction  $\mathbf{B}$  associated with a plane monochromatic electromagnetic wave whose electric field is

$$\mathbf{E} = \mathbf{E}_0 \exp i(\mathbf{k} \cdot \mathbf{r} - \omega t)$$

traveling in a homogeneous material described by a real index of refraction  $n$ . Give the relationship of  $|\mathbf{k}|$  to  $\omega$ .

- (b) [2 pts] From the above figure give  $\mathbf{k}_i$ ,  $\mathbf{k}_r$ , and  $\mathbf{k}_t$  in terms of their  $\hat{\mathbf{x}}$  and  $\hat{\mathbf{z}}$  components, and evaluate  $\mathbf{k} \cdot \mathbf{r}$  in the  $z = 0$  plane.
- (c) [1 pts] From the above figure give  $\mathbf{E}_{0i}$ ,  $\mathbf{E}_{0r}$ , and  $\mathbf{E}_{0t}$  in terms of their  $\hat{\mathbf{x}}$  and  $\hat{\mathbf{z}}$  components.
- (d) [1 pts] State the 4 boundary conditions satisfied by the fields  $\mathbf{E}$ ,  $\mathbf{B}$ ,  $\mathbf{H}$ , and  $\mathbf{D}$  at the above  $z = 0$  junction.
- (e) [1 pts] Use one of these junction conditions to prove Snell's law,  $n_t \sin \theta_t = n_i \sin \theta_i$  (only 2 of the 4 are independent).
- (f) [3 pts] Use two of the junction conditions to determine the ratio of the magnitude of the amplitudes of the reflected and transmitted to the incident electric fields, i.e., evaluate  $|\mathbf{E}_{0r}|/|\mathbf{E}_{0i}|$  and  $|\mathbf{E}_{0t}|/|\mathbf{E}_{0i}|$  as shown in the figure.

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# E+M #1

SI

\* Remember:

$$\nabla \cdot \mathbf{D} = \rho_f$$

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

$$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}_f$$

$$\mathbf{D} = \epsilon \mathbf{E}$$

$$n = \sqrt{\mu \epsilon_r} = c/v$$

$$\mathbf{B} = \mu \mathbf{H}$$

$$\mu = \mu_0 \Rightarrow \mu_r = 1$$

a) To determine the relationship b/w  $|k|$  and  $\omega$ , we derive the wave equation

$$\nabla \times (\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t}) = 0$$

$$\nabla \times \nabla \times \mathbf{E} + \frac{\partial}{\partial t} \nabla \times \mathbf{B} = 0$$

$$-\nabla^2 \mathbf{E} + \nabla(\nabla \cdot \mathbf{E}) + \frac{\partial}{\partial t} \mu (\nabla \times \mathbf{H}) = 0$$

$$-\nabla^2 \mathbf{E} + \frac{\partial}{\partial t} \mu \left( \frac{\partial}{\partial t} \mathbf{D} \right) = 0 \quad (\text{no free charges / currents})$$

$$-\nabla^2 \mathbf{E} + \mu \epsilon \frac{\partial^2}{\partial t^2} \mathbf{E} = 0$$

$$\text{* Given } \vec{E} = E_0 \exp[i(\vec{k} \cdot \vec{r} - \omega t)]$$

$$\frac{\partial^2}{\partial t^2} \mathbf{E} = -\omega^2 E_0 \exp[i(\vec{k} \cdot \vec{r} - \omega t)]$$

$$\begin{aligned} -\nabla^2 \mathbf{E} &= \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right) E_0 \exp[i(\vec{k} \cdot \vec{r} - \omega t)] \\ &= |k|^2 \exp[i(\vec{k} \cdot \vec{r} - \omega t)] \end{aligned}$$

$$|k|^2 - n^2 \omega^2 = 0 \Rightarrow |k| = n \omega$$

$$b) \vec{k}_i = \langle \sin \theta_i, 0, \cos \theta_i \rangle |k_i|$$

$$\vec{k}_r = \langle \sin \theta_r, 0, -\cos \theta_r \rangle |k_r|$$

$$\vec{k}_t = \langle \sin \theta_t, 0, \cos \theta_t \rangle |k_t|$$

# #1 (cont.)

b)  $k_i \cdot r = k_i x \sin \theta_i$

$k_r \cdot r = k_r x \sin \theta_r$

$k_t \cdot r = k_t x \sin \theta_t$

$r = (x, y, 0)$  b/c in  $z=0$  plane

c)  $\vec{E}$  must be perpendicular to  $\vec{k}$

$\vec{E}_i = E_{0,i} \langle \cos \theta_i, 0, -\sin \theta_i \rangle$

$\vec{E}_r = E_{0,r} \langle \cos \theta_r, 0, \sin \theta_r \rangle$

$\vec{E}_t = E_{0,t} \langle \cos \theta_t, 0, -\sin \theta_t \rangle$

d) Our boundary conditions are:

①  $D_1^+ - D_2^+ = \sigma_f$

③  $B_1^+ - B_2^+ = 0$

②  $E_1'' - E_2'' = 0$

④  $H_1'' - H_2'' = k_f \cdot \frac{1}{\mu_0}$

\* However, since there are no free charges

$D \cdot \hat{n}$ ,  $B \cdot \hat{n}$ ,  $E \times \hat{n}$ ,  $H \times \hat{n}$  are all continuous

e) Using boundary condition ①:

$\epsilon_1 E_1 \cdot \hat{z} = \epsilon_2 E_2 \cdot \hat{z}$

$\epsilon_1 (\vec{E}_i + \vec{E}_r) \cdot \hat{z} = \epsilon_2 (\vec{E}_t \cdot \hat{z})$

$\epsilon_1 (-E_{0,i} \sin \theta_i + E_{0,r} \sin \theta_r) \exp[i(x k_i \sin \theta_i - \omega t)] = \epsilon_2 E_L \sin \theta_t \exp[i(\underline{k_t \sin \theta_t} - \omega t)]$

$x k_i \sin \theta_i = x k_t \sin \theta_t$

$n_i \sin \theta_i = n_t \sin \theta_t$

#1 (cont.)

f) \* From part e we know

$$E_i (E_r - E_t) \sin \theta_i = E_t \sin \theta_t$$

$$\cancel{n_i} (E_r - E_t) \sin \theta_i = \cancel{n_t} E_t \sin \theta_t$$

\* using our  $E \times \hat{n}$  boundary condition:

$$(E_i + E_r) \cos \theta_i = E_t \cos \theta_t$$

\* Thus:

$$(1) \quad n_i (E_r - E_t) = n_t E_t$$

$$(2) \quad (E_i + E_r) \cos \theta_i = E_t \cos \theta_t$$

\* Solving for  $E_r$ :

$$(E_i + E_r) \cos \theta_i = \frac{n_i}{n_t} (E_r - E_t) \cos \theta_t$$

$$E_i (\cos \theta_i + \frac{n_i}{n_t} \cos \theta_t) = E_r (\frac{n_i}{n_t} \cos \theta_t - \cos \theta_i)$$

$$\frac{E_r}{E_i} = \frac{n_i/n_t \cos \theta_t - \cos \theta_i}{\cos \theta_i - n_i/n_t \cos \theta_t} = \frac{n_i \cos \theta_t - n_t \cos \theta_i}{n_t \cos \theta_i - n_i \cos \theta_t}$$

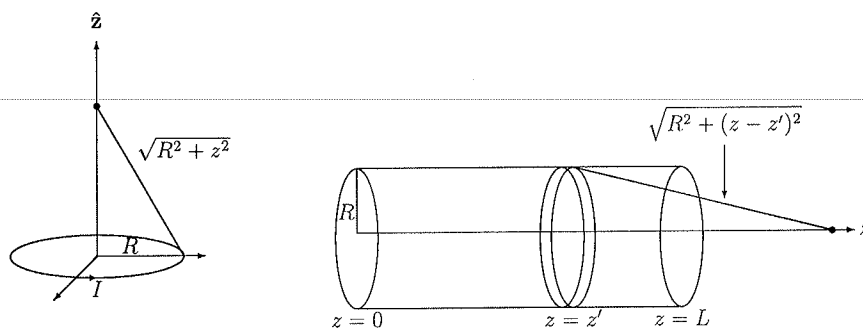
\* Solving for  $E_t$

$$E_r = \frac{n_t}{n_i} E_t + E_i$$

$$(2E_i + \frac{n_t}{n_i} E_t) \cos \theta_i = E_t \cos \theta_t$$

$$2E_i \cos \theta_i = E_t (\cos \theta_t - \frac{n_t}{n_i} \cos \theta_i)$$

$$\frac{E_t}{E_i} = \frac{\cos \theta_t - \frac{n_t}{n_i} \cos \theta_i}{2 \cos \theta_i}$$



2. (a) [3 pts] A circular loop of radius  $R$ , centered on the origin and  $z = 0$  plane, carries a current  $I$ . Find the magnetic field  $B$  on the axis of the loop as a function of the distance  $z$  from the center of the loop.
- (b) [4 pts] Use the result of part (a) to find  $B$  along the axis of a solenoid of radius  $R$  and length  $L$ , uniformly wound with  $n = N/L$  turns per unit length.
- (c) [3 pts] Assume that instead of a solenoid you had a cylinder of radius  $R$  and length  $L$  made out of a piece of uniformly magnetized iron with magnetization  $\mathbf{M}$  pointing along the axis of the solenoid. Use the solution of part (b) to calculate the magnetic field strength  $\mathbf{H}$  and the magnetic induction  $\mathbf{B}$  along the axis of the cylinder, both inside and outside.

HINTS:

$$\int \frac{dw}{[R^2 + w^2]^{3/2}} = \frac{w}{\sqrt{R^2 + w^2}} + \text{constant}.$$

The bound volume and surface current densities associated with a smooth magnetization density are respectively

$$\mathbf{J}_b|_{SI} = \nabla \times \mathbf{M},$$

and

$$\mathbf{K}_b|_{SI} = \mathbf{M} \times \mathbf{n},$$

where  $\mathbf{n}$  is the outward unit normal at the magnet's boundary. The Gaussian expressions for  $\mathbf{J}_b$  and  $\mathbf{K}_b$  contain an additional factor of  $c$  in the numerators.

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# E+M #2

SI

a) We can use Biot-Savart Law to determine  $\vec{B}$

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{\vec{J} \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3} d\vec{r}'$$

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{I d\vec{\ell} \hat{\phi} \times (\vec{r} - \vec{r}')}{(R^2 + z^2)^{3/2}}$$

\* evaluate cross product:

$$\begin{vmatrix} \hat{r} & \hat{\phi} & \hat{z} \\ 0 & d\ell & 0 \\ R & 0 & z \end{vmatrix} = \hat{z} d\ell, 0, R d\ell$$

$$\vec{B} = \frac{\mu_0}{4\pi} \int \frac{I R d\ell}{(R^2 + z^2)^{3/2}} \hat{z} \quad (\text{ignore } \hat{r} \text{ component due to symmetry})$$

$$= \frac{\mu_0 2\pi R^2 I}{4\pi (R^2 + z^2)^{3/2}} \hat{z}$$

$$= \frac{\mu_0 I R^2}{2 (R^2 + z^2)^{3/2}} \hat{z}$$

b) \* Typically, when going from current loop to solenoid,  $I \rightarrow I_n dz$ . Also, because our solenoid is of a finite length,  $z \rightarrow z - z'$

$$\hookrightarrow d\vec{B} = \frac{\mu_0 n I dz' R^2}{2 (R^2 + (z - z')^2)^{3/2}} \hat{z}$$

$$B = \frac{\mu_0 n I}{2} \int_0^L \frac{R^2 dz' \hat{z}}{(R^2 + (z - z')^2)^{3/2}}$$

$$= \frac{\mu_0 n I R^2}{2} \left[ \frac{z'}{(R^2 + (z - z')^2)^{1/2}} \right]_0^L$$

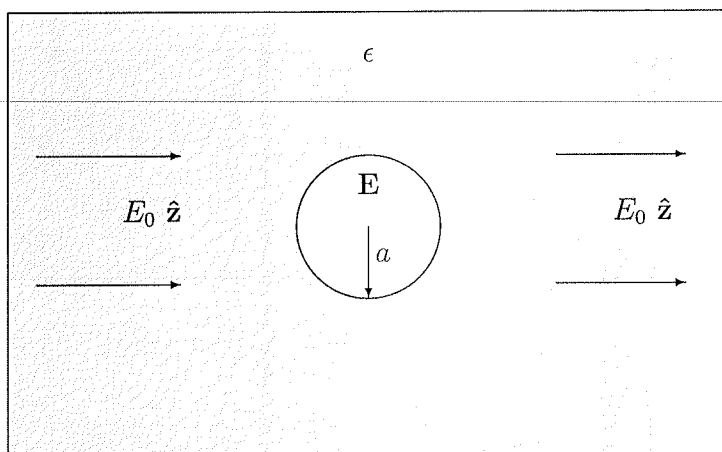
$$= \frac{\mu_0 n I R^2 L}{2 (R^2 + (z - L)^2)^{1/2}}$$

#2 (cont.)

c)

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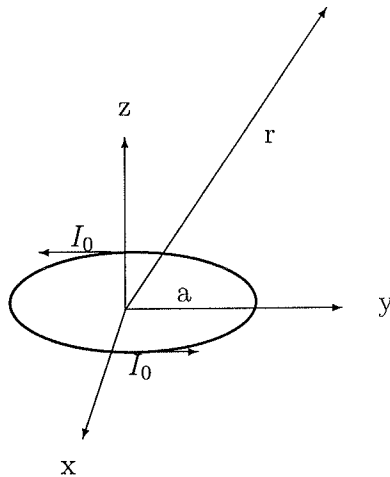
3. A small spherical vacuum bubble of radius  $a$  exists inside an otherwise homogeneous dielectric material whose electric polarization properties are described by a constant permittivity  $\epsilon$ . Assume the bubble is centered on the origin and that the electric field far from vacuum bubble but still in the homogeneous material is of the form  $\mathbf{E} = E_0 \hat{z}$ . Because of the axial symmetry the electrostatic potential  $\Phi(r, \theta)$  for this problem can be written as a linear combination of constants times Legendre polynomials.
  - (a) [2 pts] What are the boundary conditions satisfied by the fields  $\mathbf{E}$  and  $\mathbf{D}$  fields, and the potential  $\Phi$  at the junction  $r = a$ ?
  - (b) [2 pts] Give the electrostatic potential inside the bubble as a combination of constants and Legendre polynomials (keep only non-vanishing  $\ell$  terms).
  - (c) [2 pts] Give the electrostatic potential outside the bubble as a combination of constants and Legendre polynomials (keep only non-vanishing  $\ell$  terms).
  - (d) [2 pts] Use the boundary conditions at the  $r = a$  junction from part (a) to evaluate the non-vanishing constants in parts (b) and (c).
  - (e) [2 pts] Express the electric field outside the bubble as an electric dipole field plus the uniform field  $E_0 \hat{z}$  and give the value of the dipole moment.

4. (a) [2 pts] Write down any vector potential that produces the uniform magnetic induction

$$\mathbf{B} = B_0 \hat{\mathbf{z}}.$$

- (b) [4 pts] What is the magnetic induction  $\mathbf{B}$  and an associated vector potential  $\mathbf{A}$  ( $\mathbf{B} = \nabla \times \mathbf{A}$ ) produced by a very long wire located on the  $z$ -axis and carrying a current  $I_0$  in the  $+z$  direction?
- (c) [4 pts] A small circular loop of wire of radius  $a$ , centered at the origin and lying in the  $z = 0$  plane, carries a current  $I_0$  as shown in the figure. Derive an approximate expression for the vector potential at large distances ( $r \gg a$ ) from the loop. Recall that

$$\frac{1}{|\mathbf{r} - \mathbf{r}'|} \approx \frac{1}{r} \left\{ 1 + \frac{\mathbf{r} \cdot \mathbf{r}'}{r^2} + \mathcal{O}\left(\frac{r'}{r}\right)^2 \right\}$$



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# E+M #4

a) We know that  $\nabla \times \vec{A} = \vec{B}$ , therefore if  $B_z = B_0 \hat{z}$

$$\begin{aligned} B_z &= \partial_x A_y - \partial_y A_x \Rightarrow \text{set } A_z = 0 \\ &= \frac{\partial}{\partial x} \frac{B_0}{2} x - \frac{\partial}{\partial y} \left( -\frac{B_0}{2} y \right) \\ &= \frac{B_0}{2} + \frac{B_0}{2} \\ &= B_0 \checkmark \end{aligned}$$

$$\Rightarrow \vec{A} = \left\langle -\frac{B_0}{2} y, \frac{B_0}{2} x, 0 \right\rangle$$

b) \* We first solve for  $\vec{B}$



$$\int \vec{B} \cdot d\vec{l} = \frac{4\pi}{c} I_0$$

$$\vec{B} \cdot 2\pi r = \frac{4\pi}{c} I_0$$

$$\vec{B} = \frac{2I_0}{cr} \hat{\phi}$$

$$= \vec{\nabla} \times \vec{A}$$

$$\vec{\nabla} \times \vec{A} = \left\langle \frac{1}{r} \frac{\partial A_z}{\partial \phi} - \frac{\partial A_\phi}{\partial z}, \frac{\partial A_\phi}{\partial z} - \frac{\partial A_z}{\partial r}, \frac{1}{r} \left( \frac{\partial}{\partial r} (A_r) - \frac{\partial A_r}{\partial \phi} \right) \right\rangle$$

$\hookrightarrow$  set  $A_\phi = 0$ ;  $A_r, A_z$  has no  $\phi$  dependence

$$= \frac{2I_0}{c} \left\langle \frac{1}{r} \frac{\partial A_z}{\partial \phi}, \frac{\partial A_\phi}{\partial z} - \frac{\partial A_z}{\partial r}, \frac{1}{r} \frac{\partial A_r}{\partial \phi} \right\rangle$$

$$= \frac{2I_0}{c} \langle 0, \frac{\partial A_\phi}{\partial z} - \frac{\partial A_z}{\partial r}, 0 \rangle$$

$$\hookrightarrow \frac{1}{r} = \frac{\partial A_\phi}{\partial z} - \frac{\partial A_z}{\partial r}$$

\* since an arbitrary  $A$  works, set  $A_\phi = 0$ ,

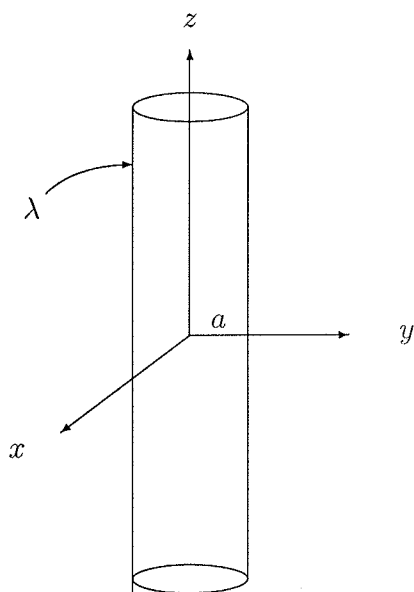
$$\int \frac{1}{r} dr = \int \frac{\partial A_z}{\partial r} dr$$

$$\ln(r) = A_z$$

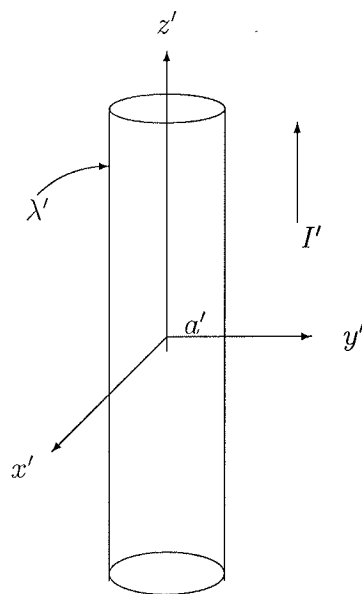
$$\Rightarrow \vec{A} = \frac{2I_0}{c} \langle 0, 0, \ln(r) \rangle$$

5. An infinitely long, uniformly charged wire of radius  $a$  and total charge per unit length  $\lambda$ , is at rest on the  $z$ -axis of the lab frame.

- (a) [2 pts] Compute the electric field  $\mathbf{E}(x, y, z)$  exterior to the wire in the lab frame by solving Gauss's law in that frame. What is the magnetic induction  $\mathbf{B}(x, y, z)$  in this frame?
- (b) [2 pts] If you are moving in the lab's negative  $z$  direction with speed  $v$  how are your spatial and time coordinates related to those of the lab's? To answer this question simply give the Lorentz boost  $x'^{\sigma} = L^{\sigma}_{\mu} x^{\mu}$  that relates the two sets of coordinates.
- (c) [2 pts] In your frame what is the radius  $a'$  of the wire? What is the charge/length  $\lambda'$  of the wire and what is the current  $I'$  in the wire?
- (d) [1 pts] Combine the  $E$  and  $B$  fields in the lab into a single electromagnetic field tensor  $F^{\alpha\beta}$  using  $F^{\sigma\mu} = -F^{\mu\sigma}$  and  $F^{0i} = -E^i$ . In Gaussian units  $F^{12} = -B^z$ ,  $F^{23} = -B^x$  and  $F^{13} = B^y$ , and in SI units  $F^{12} = -c B^z$ ,  $F^{23} = -c B^x$  and  $F^{13} = c B^y$ .
- (e) [3 pts] What electric field  $\mathbf{E}'(x', y', z')$  and what magnetic induction  $\mathbf{B}'(x', y', z')$  will you measure exterior to the wire in your frame? To answer this part you can use your answers for part (c) or you can compute  $F' = L F L^T$ .



Lab



Moving Frame

Aug 2013

E + M # 5

a) From Gauss Law, we know that

$$\int \vec{E} \cdot d\vec{a} = \frac{q}{\epsilon_0}$$

$$E \int da = \frac{\lambda L}{\epsilon_0}$$

$$E(2\pi r L) = \frac{\lambda L}{\epsilon_0}$$

$$\vec{E} = \frac{1}{2\pi\epsilon_0} \frac{\lambda}{r} \hat{r}$$

\* However, we must convert this from cylindrical coordinates to cartesian

$$\Rightarrow r = \sqrt{x^2 + y^2}$$

$$\hat{r} = \cos\phi \hat{x} + \sin\phi \hat{y}$$

$$\hookrightarrow \vec{E}(x, y, z) = \frac{\lambda}{2\pi\epsilon_0} \frac{\langle \cos\phi, \sin\phi, 0 \rangle}{\sqrt{x^2 + y^2}}$$

\* Since there is no moving charge in the wire,  $\vec{B} = 0$

b) In a moving frame, we know coordinates are transformed according to:

$$x'^{\sigma} = L^{\sigma}_{\mu} x^{\mu} \quad \Leftrightarrow \quad x' = L_z x$$

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma ct + \gamma\beta z \\ x \\ y \\ \gamma\beta ct + \gamma z \end{bmatrix} \quad \Rightarrow \quad \begin{aligned} t' &= \frac{\gamma}{c} (ct + \beta z) \\ x' &= x \\ y' &= y \\ z' &= \gamma(\beta ct + z) \end{aligned}$$

## #5(cont.)

- c) \* Since the radius of the wire only depends on  $x$  and  $y$ , it is unchanged moving from the unprimed frame to the primed frame.

\* We can transform the current vector to find  $\lambda'$  and  $I'$

$$\vec{J} = \begin{bmatrix} c\lambda \\ J_x \\ J_y \\ J_z \end{bmatrix} = \begin{bmatrix} c\lambda \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\vec{J}' = L_z J$$

$$= \begin{bmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} c\lambda \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$= \begin{bmatrix} c\lambda\gamma \\ 0 \\ 0 \\ \gamma\beta c\lambda \end{bmatrix}$$

$$\Rightarrow c\lambda' = c\lambda\gamma \rightarrow \lambda' = \gamma\lambda$$

$$J'_z = \gamma\beta c\lambda$$

$$I' = \oint \vec{J}' \cdot d\vec{a}'$$

$$= J'_z \cdot \pi a^2$$

$$= \gamma\beta c\lambda \pi a^2$$

- d) In the lab (unprimed) frame, our field tensor is:

$$F^{\alpha\beta} = \begin{bmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -cB_z & cB_y \\ E_y & cB_z & 0 & -cB_x \\ E_z & -cB_y & cB_x & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -E_x & -E_y & 0 \\ E_x & 0 & 0 & 0 \\ E_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$E_x = \frac{\lambda \cos \phi}{2\pi\epsilon_0 \sqrt{x^2 + y^2}}$$

$$E_y = \frac{\lambda \sin \phi}{2\pi\epsilon_0 \sqrt{x^2 + y^2}}$$

#5 (cont.)

e) The field tensor  $B$  transformed according to:

$$F' = L F L^T$$

$$= \begin{bmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} 0 & -E_x & -E_y & 0 \\ E_x & 0 & 0 & 0 \\ E_y & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{bmatrix}$$

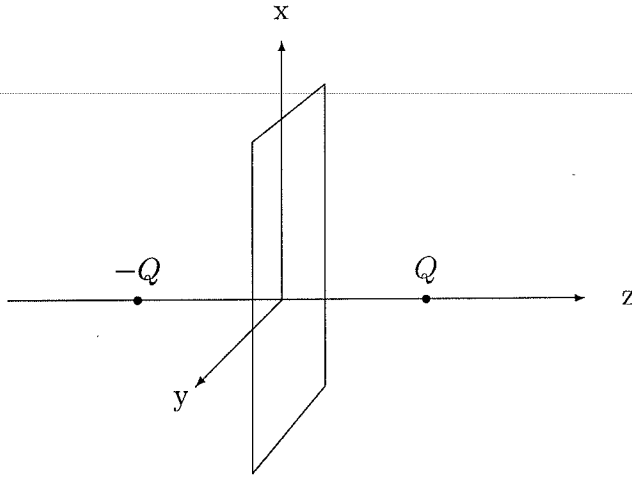
$$= \begin{bmatrix} \gamma & 0 & 0 & \gamma\beta \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \gamma\beta & 0 & 0 & \gamma \end{bmatrix} \begin{bmatrix} 0 & -E_x & -E_y & 0 \\ \gamma E_x & 0 & 0 & \gamma\beta E_x \\ \gamma E_y & 0 & 0 & \gamma\beta E_y \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -\gamma E_x & -\gamma E_y & 0 \\ \gamma E_x & 0 & 0 & \gamma\beta E_x \\ \gamma E_y & 0 & 0 & \gamma\beta E_y \\ 0 & -\gamma\beta E_x & -\gamma\beta E_y & 0 \end{bmatrix}$$

$$\Rightarrow \begin{aligned} E_x' &= \gamma E_x & E_z' &= 0 \\ E_y' &= \gamma E_y & B_z' &= 0 \\ B_y' &= \frac{\gamma\beta}{c} E_x \\ B_x' &= -\frac{\gamma\beta}{c} E_y \end{aligned}$$

$$\Rightarrow \vec{E} = \frac{\gamma\lambda}{2\pi\epsilon_0\sqrt{x^2+y^2}} \langle \cos\phi \hat{x}, \sin\phi \hat{y}, 0 \rangle$$

$$\vec{B} = \frac{\gamma\beta\lambda}{c2\pi\epsilon_0\sqrt{x^2+y^2}} \langle \sin\phi \hat{x}, -\cos\phi \hat{y}, 0 \rangle$$



6. This problem requires the use of Maxwell's stress tensor  $T_M^{ij}$ .

- (a) [3 pts] Compute Maxwell's stress tensor  $T_M^{ij}$  on the  $z = 0$  plane for a system of two equal and opposite point charges ( $\pm Q$ ) located on the  $z$ -axis at  $\mathbf{r} = (0, 0, \pm b)$  as shown in the figure. For this application

$$T_M^{ij}|_{\text{Gaussian}} = \left( \frac{1}{4\pi} \right) \left[ E^i E^j - \frac{\delta^{ij}}{2} E^2 \right],$$

or

$$T_M^{ij}|_{\text{SI}} = (\epsilon_0) \left[ E^i E^j - \frac{\delta^{ij}}{2} E^2 \right].$$

- (b) [4 pts] Evaluate the surface integral

$$\int \int T_M^{ij} dA^j = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} T_M^{iz} dx dy,$$

over the  $z = 0$  plane.

Hint: Use cylindrical polar coordinates to do the integral.

- (c) [3 pts] The following surface integral over the boundary of a closed volume  $V_3$  is the total electromagnetic force on the E&M fields and their sources contained within that volume

$$F^i = \int_{\partial V_3} T_M^{ij} dA^j.$$

Use this fact to explain your answer to part (b).