

# Seniorensseminar

22.05.2015 KIT

## Energie- und Impulstransport in laufenden und stehenden elektromagnetischen Wellen

Wilhelm-Hausenstein-Gymnasium

Durmersheim

Didaktik der Physik KIT

[michael@pohlig.de](mailto:michael@pohlig.de)

A Elektromagnetische Welle

B stehende elektromagnetische Welle

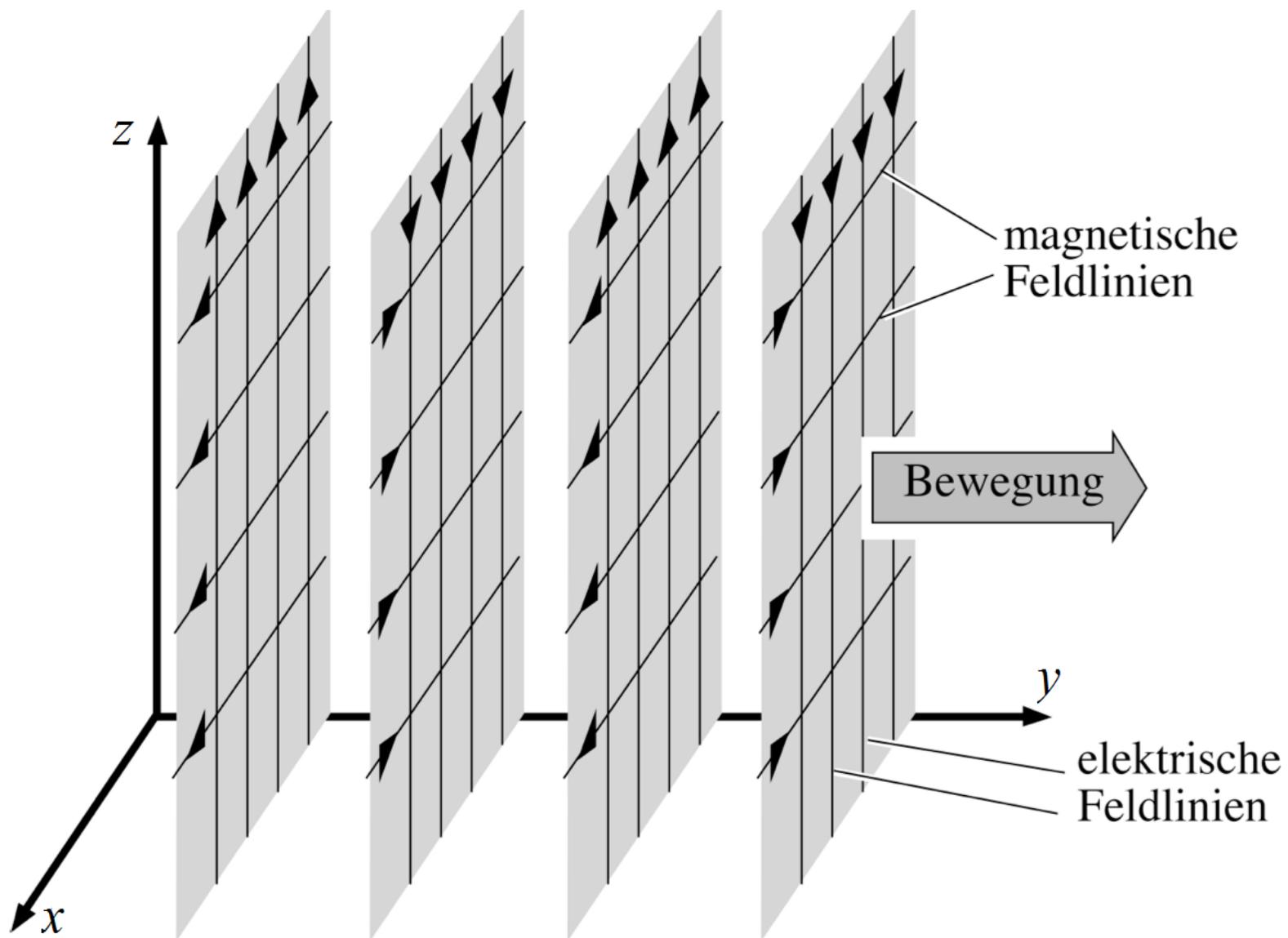
# A Elektromagnetische Welle

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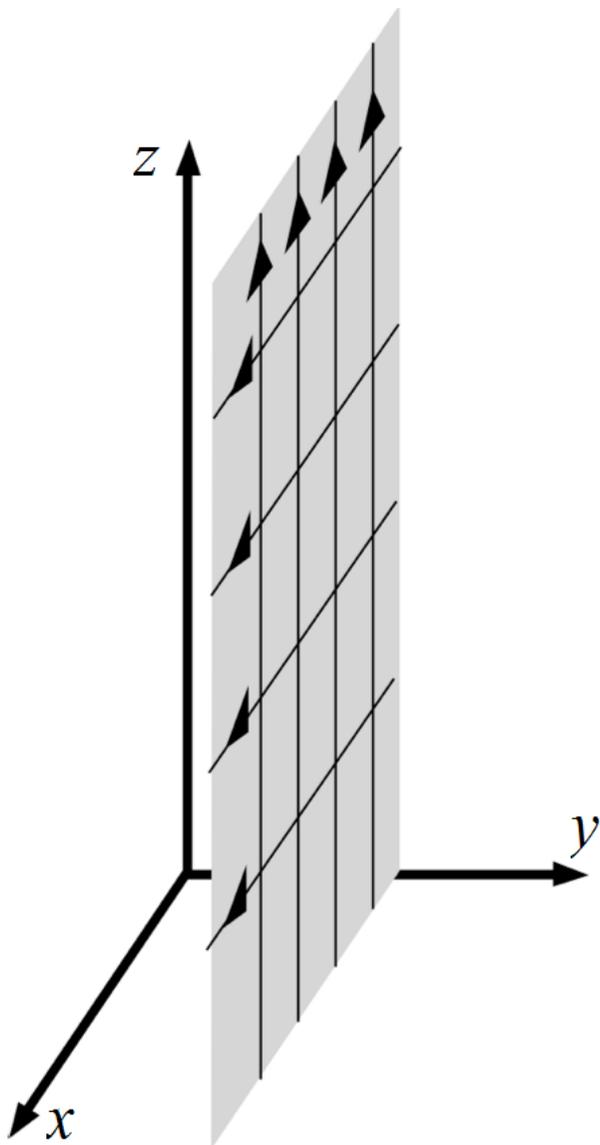
1. Ebene elektromagnetische Welle
2. Maxwell'sche Spannungstensor
3. Impulsstromdichte und Energiestromdichte
4. Light-Version

# 1. Ebene elektromagnetische Welle

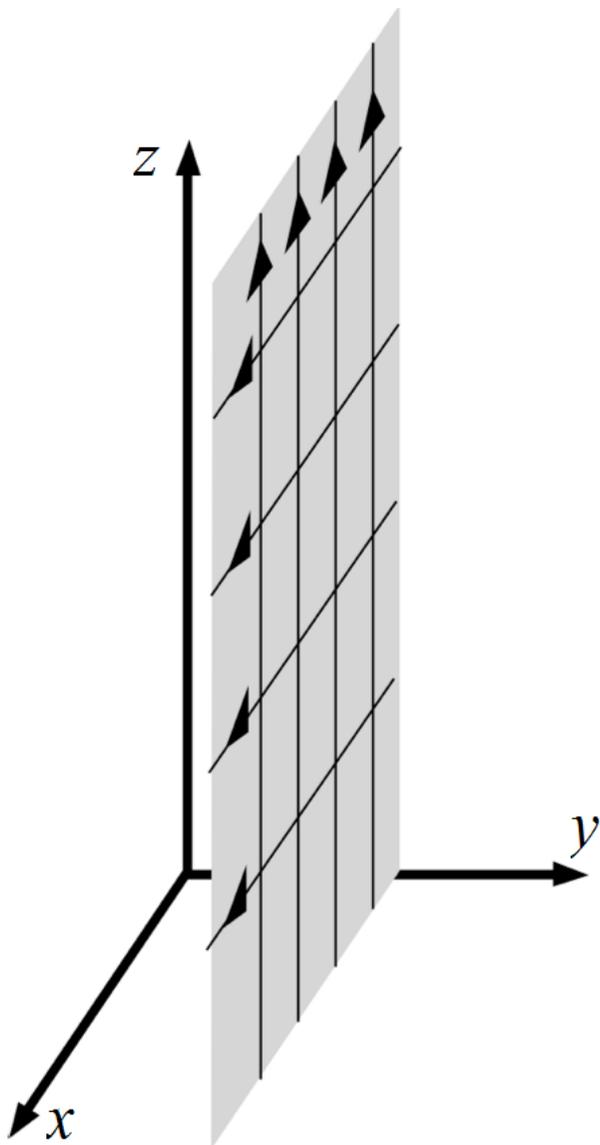
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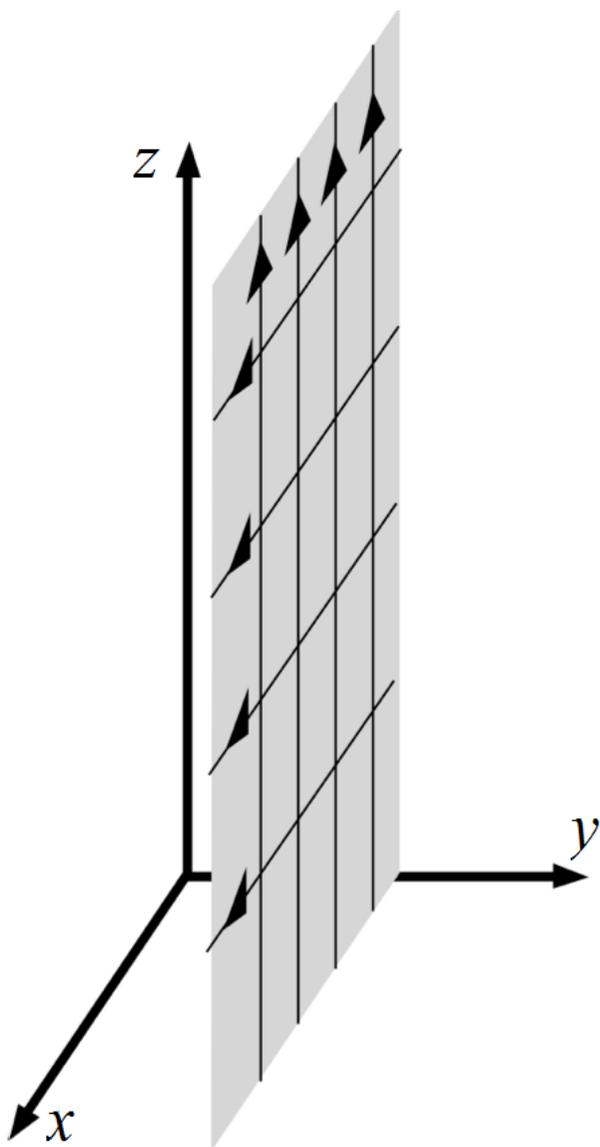


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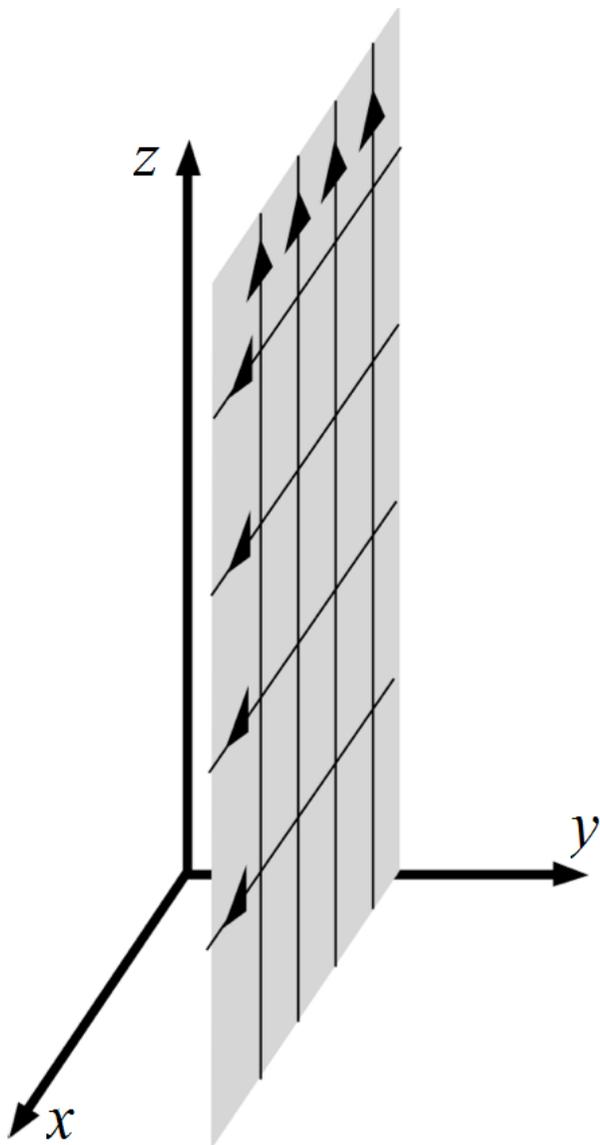
$$\vec{E} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix}$$

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$$\vec{E} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix} \quad \vec{H} = \begin{pmatrix} H_x \\ 0 \\ 0 \end{pmatrix}$$

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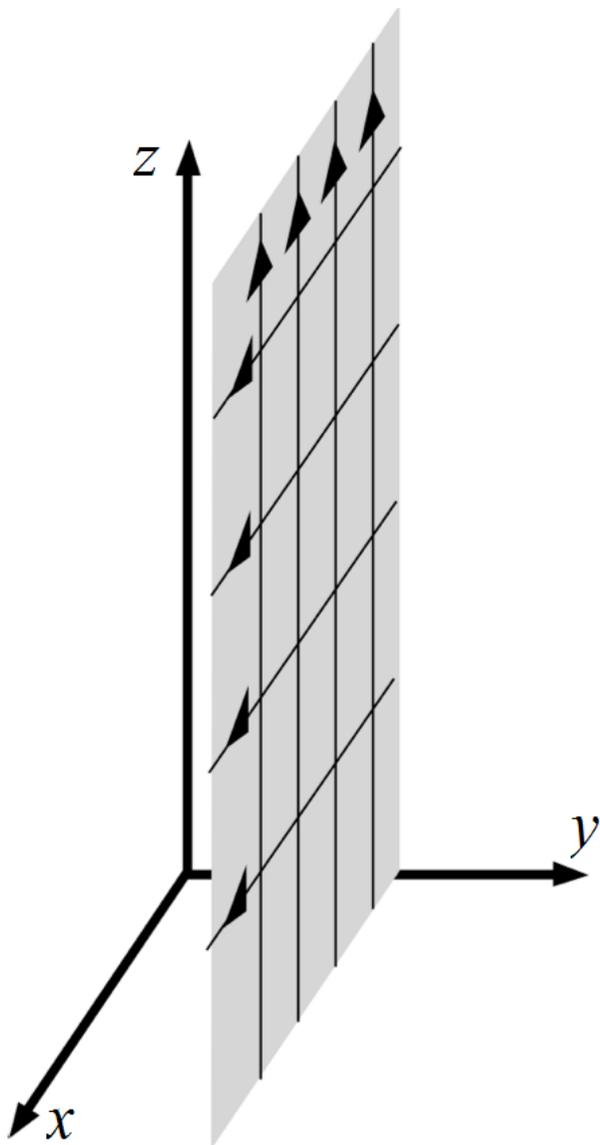
$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$

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## 2. Maxwell'sche Spannungstensor

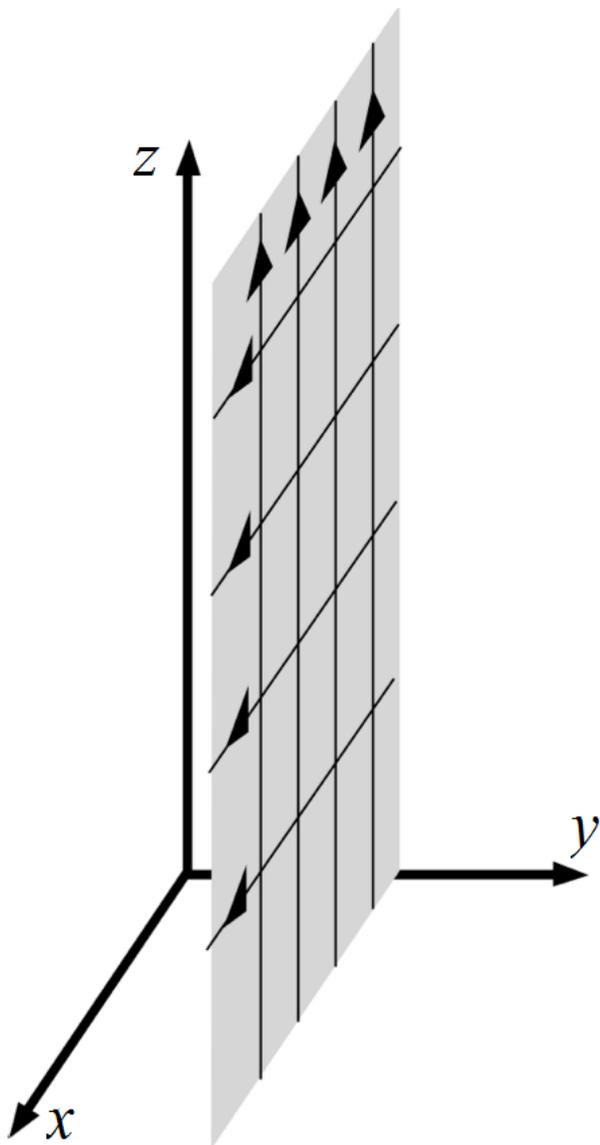
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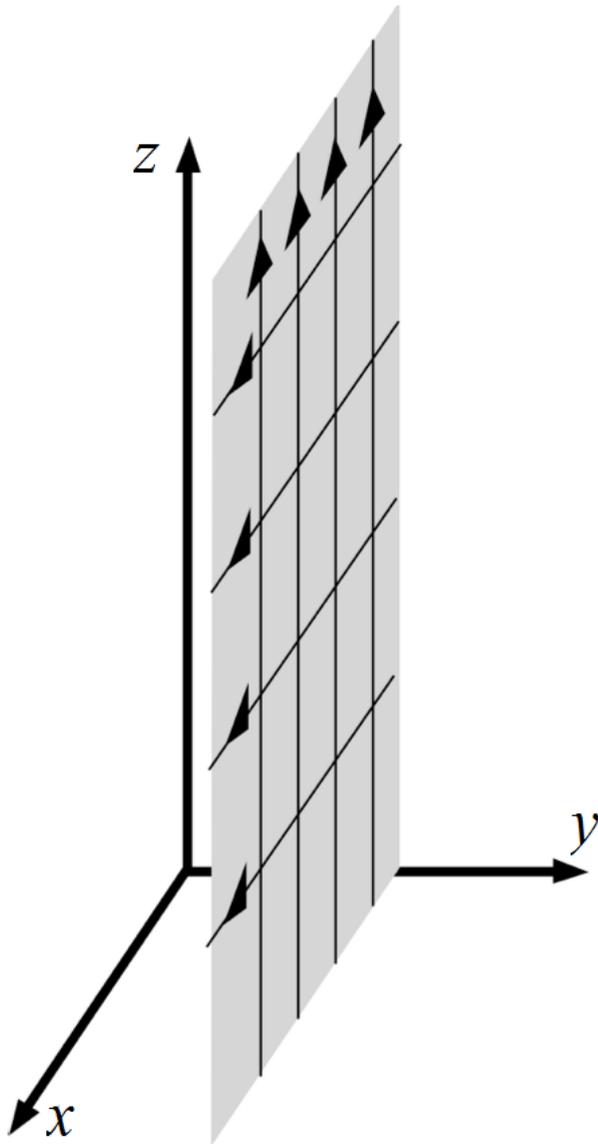
## 2. Maxwell'sche Spannungstensor



$$\vec{E} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix} \quad \vec{H} = \begin{pmatrix} H_x \\ 0 \\ 0 \end{pmatrix}$$

$$\vec{\sigma} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{pmatrix}$$

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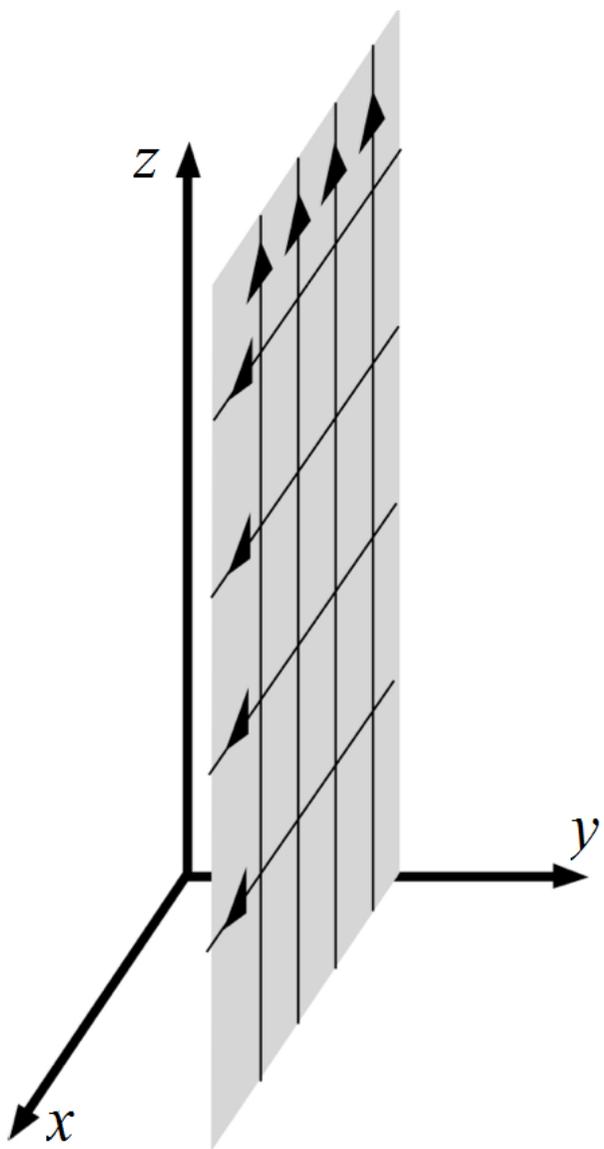


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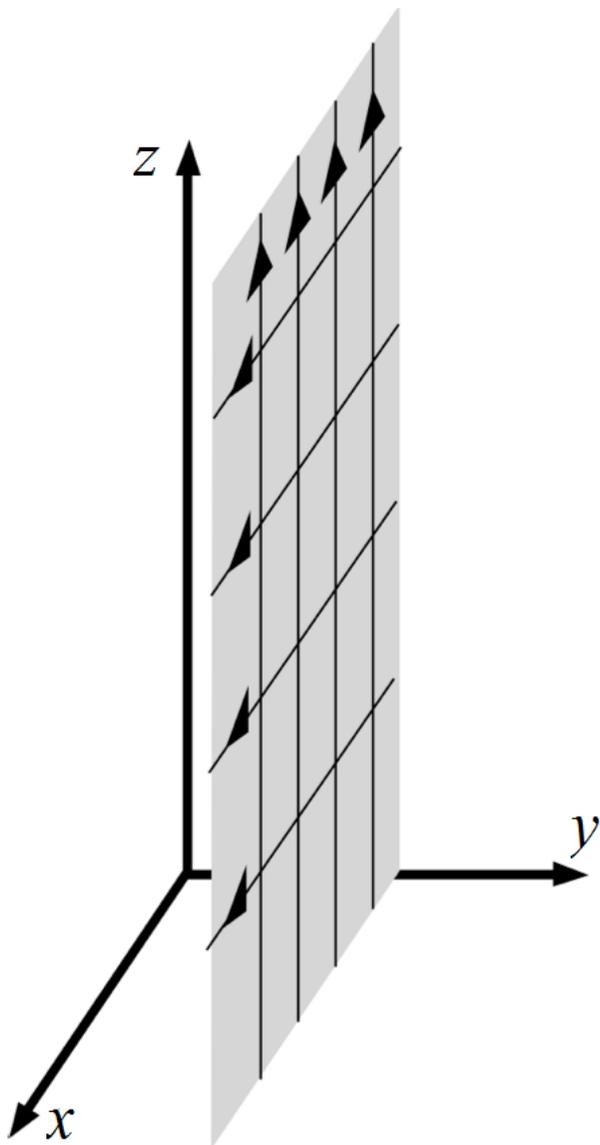
$$\sigma_{ij} = \varepsilon_0 E_i E_j + \mu_0 H_i H_j - \frac{1}{2} \delta_{ij} (\varepsilon_0 \vec{E}^2 + \mu_0 \vec{H}^2)$$

## 2. Maxwell'sche Spannungstensor



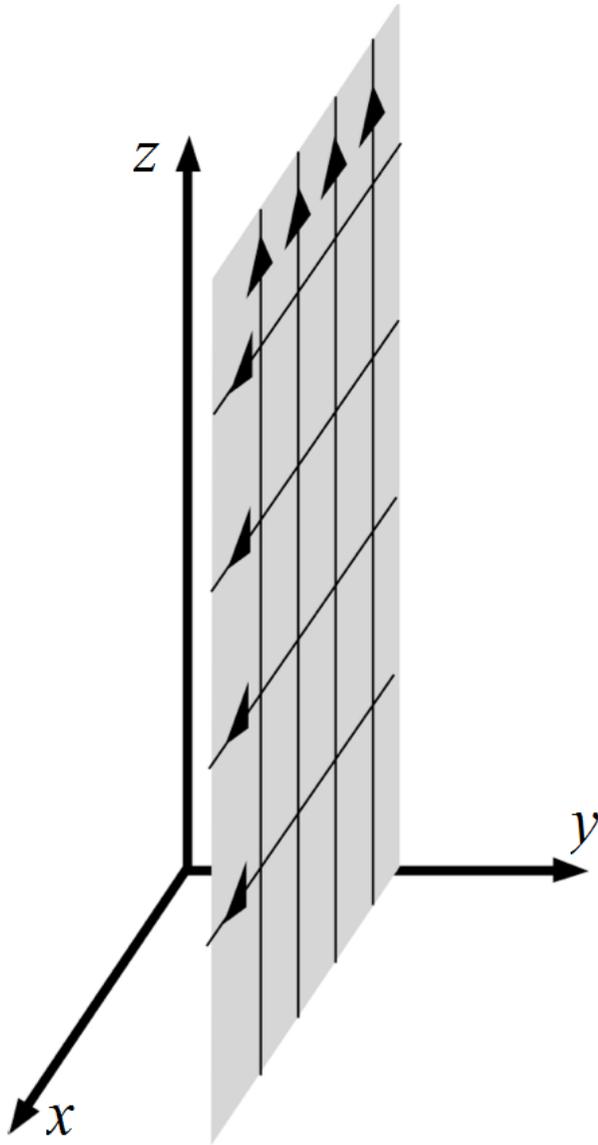
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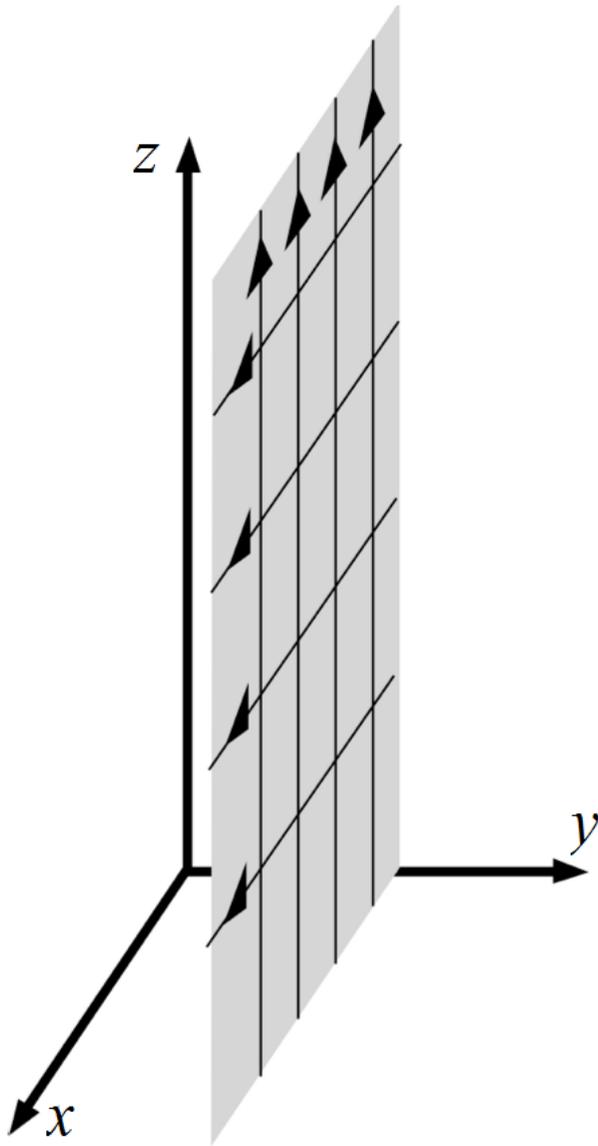
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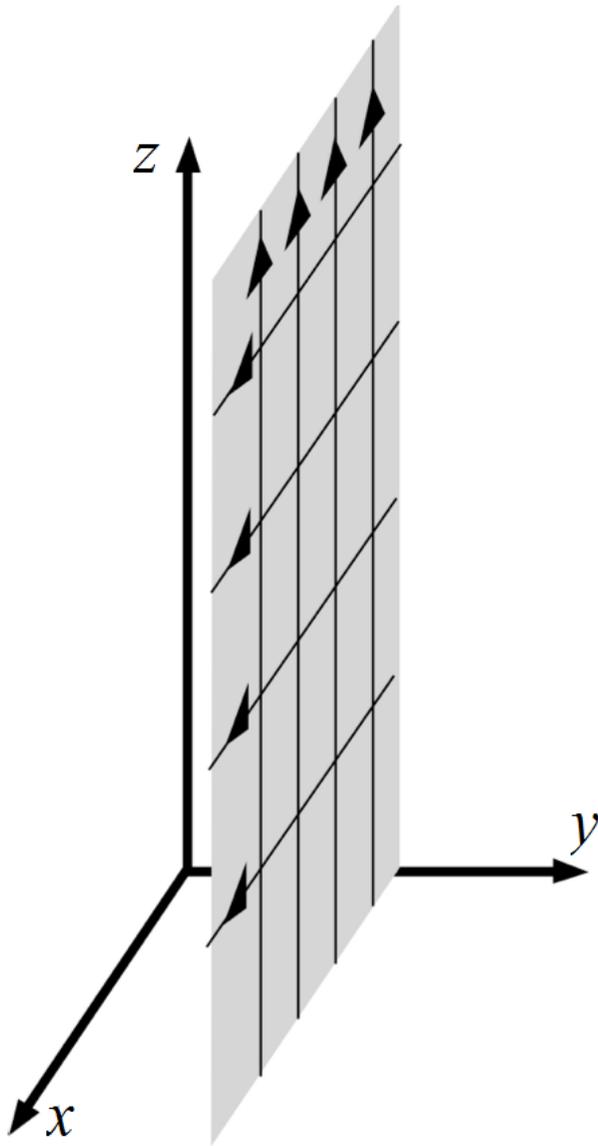
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$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$

## 2. Maxwell'sche Spannungstensor



$$\sigma_{ij} = \epsilon_0 E_i E_j + \mu_0 H_i H_j - \frac{1}{2} \delta_{ij} (\epsilon_0 \bar{E}^2 + \mu_0 \bar{H}^2)$$

$$\bar{\vec{E}} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix}$$

$$\sigma_{xx} = \mu_0 H_x^2 - \frac{\epsilon_0}{2} E_z^2 - \frac{\mu_0}{2} H_x^2 = 0$$

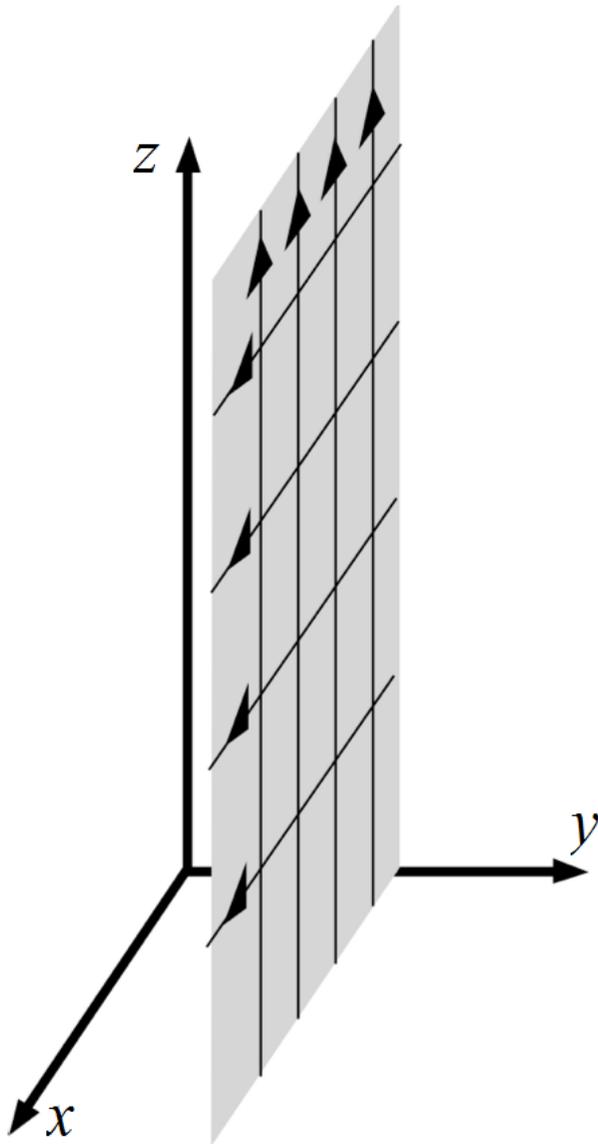
$$\bar{\vec{H}} = \begin{pmatrix} H_x \\ 0 \\ 0 \end{pmatrix}$$

$$\sigma_{xy} = 0$$

$$\sigma_{xz} = 0$$

$$\frac{\epsilon_0}{2} \bar{E}^2 = \frac{\mu_0}{2} \bar{H}^2$$

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$$\sigma_{ij} = \varepsilon_0 E_i E_j + \mu_0 H_i H_j - \frac{1}{2} \delta_{ij} (\varepsilon_0 \bar{E}^2 + \mu_0 \bar{H}^2) \quad \bar{E} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix}$$

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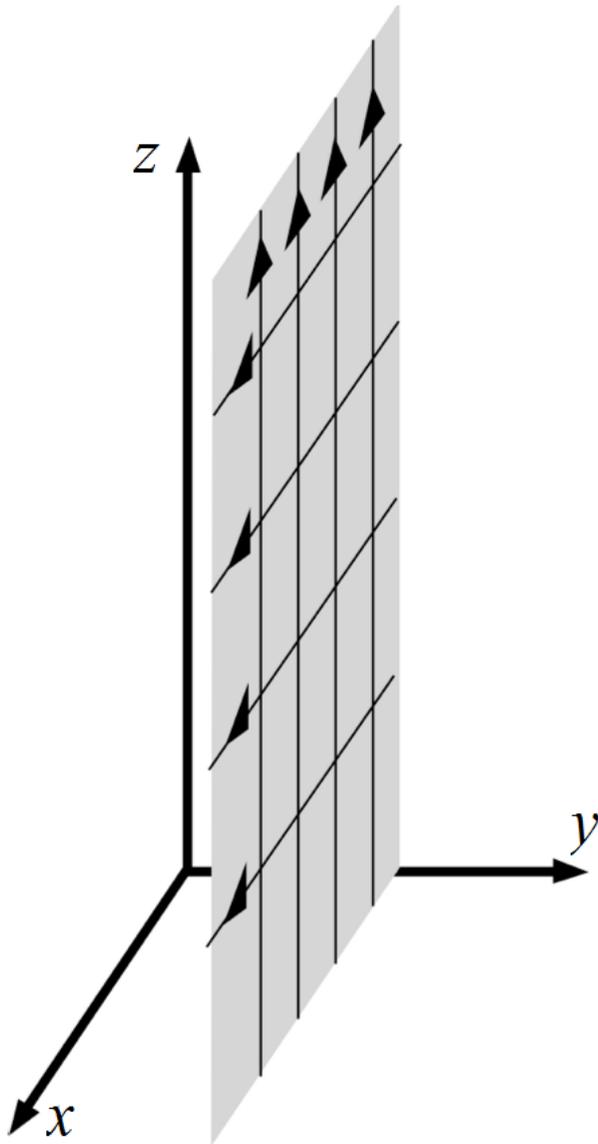
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$$\sigma_{yy} = -\frac{\varepsilon_0}{2} E_z^2 - \frac{\mu_0}{2} H_x^2 = -\varepsilon_0 E_z^2 = -\mu_0 H_x^2 = -\sqrt{\varepsilon_0 \mu_0} E_z H_x$$

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## 2. Maxwell'sche Spannungstensor



$$\sigma_{ij} = \varepsilon_0 E_i E_j + \mu_0 H_i H_j - \frac{1}{2} \delta_{ij} (\varepsilon_0 \bar{E}^2 + \mu_0 \bar{H}^2) \quad \bar{E} = \begin{pmatrix} 0 \\ 0 \\ E_z \end{pmatrix}$$

$$\sigma_{xx} = \mu_0 H_x^2 - \frac{\varepsilon_0}{2} E_z^2 - \frac{\mu_0}{2} H_x^2 = 0 \quad \bar{H} = \begin{pmatrix} H_x \\ 0 \\ 0 \end{pmatrix}$$

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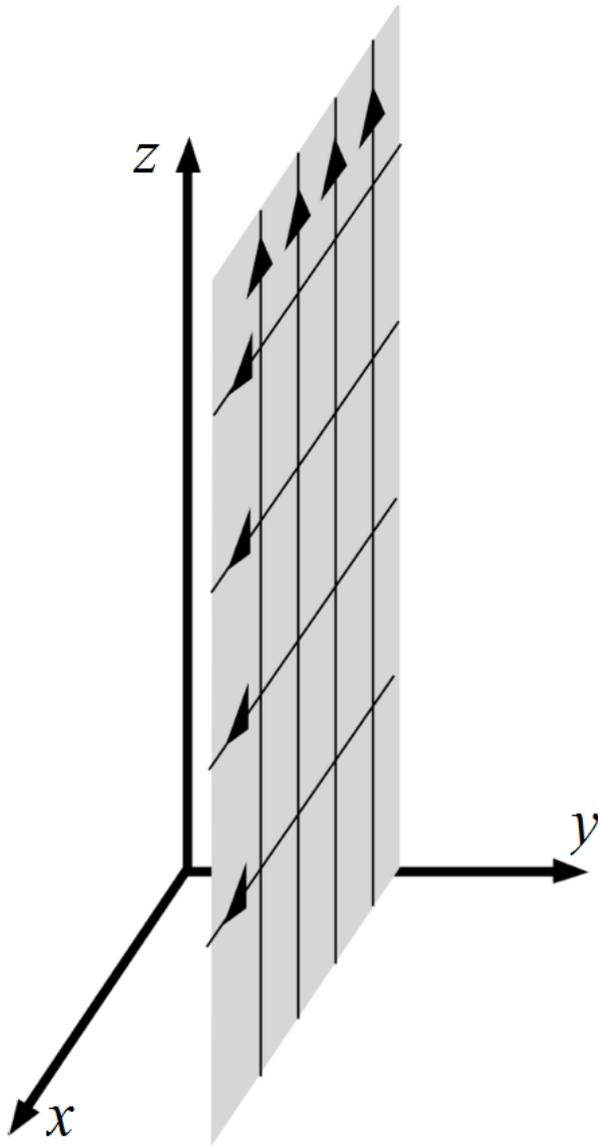
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$$\sigma_{zy} = 0$$

$$\sigma_{zz} = \varepsilon_0 E_z^2 - \frac{\varepsilon_0}{2} E_z^2 - \frac{\mu_0}{2} H_x^2 = \frac{\varepsilon_0}{2} E_z^2 - \frac{\mu_0}{2} H_x^2 = 0$$

## 2. Maxwell'sche Spannungstensor



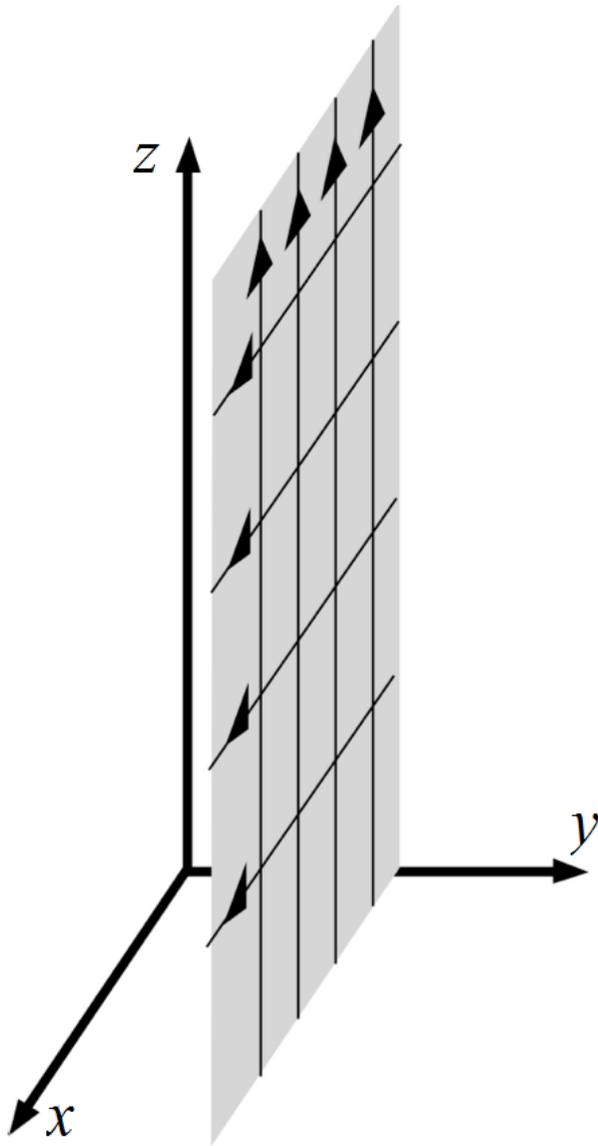
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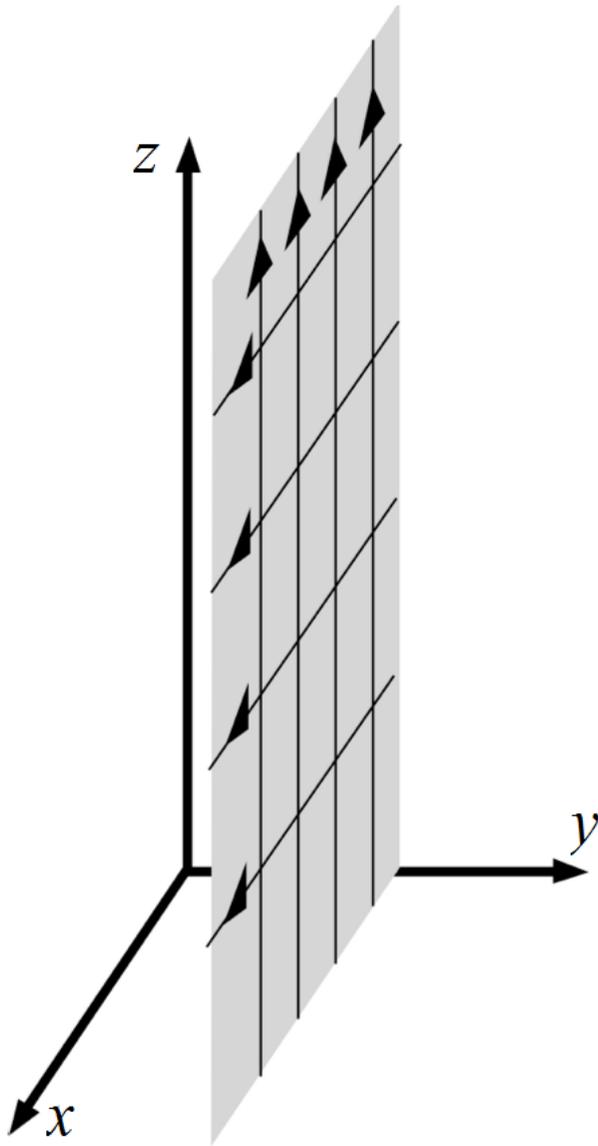
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### 3. Impulsstromdichte und Energiestromdichte

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$$\vec{j}_p = -\vec{\sigma} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sqrt{\epsilon_0 \mu_0} E_z H_x & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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$\vec{j}_x$

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$\vec{j}_x$        $\vec{j}_y$

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$$\begin{matrix} \vec{j}_x & \vec{j}_y & \vec{j}_z \end{matrix}$$

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Es strömt nur  $y$ -Impuls nur in  $y$ -Richtung.  
Impulsstromdichte:

$$j_{p_y, y} = \sqrt{\epsilon_0 \mu_0} E_z H_x$$

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Energiestromdichte:

$$j_{E,y} = E_z H_x$$

$$j_{E,y} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} j_{p_y,y}$$

### 3. Impulsstromdichte und Energiestromdichte

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Es strömt Energie nur in  $y$ -Richtung:  
Energiestromdichte:

$$j_{E,y} = E_z H_x$$

$$j_{E,y} = \frac{1}{\sqrt{\epsilon_0 \mu_0}} j_{p_y,y}$$

$$j_{E,y} = c \cdot j_{p_y,y}$$

### 3. Impulsstromdichte und Energiestromdichte

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$$I_E = c \cdot I_p$$

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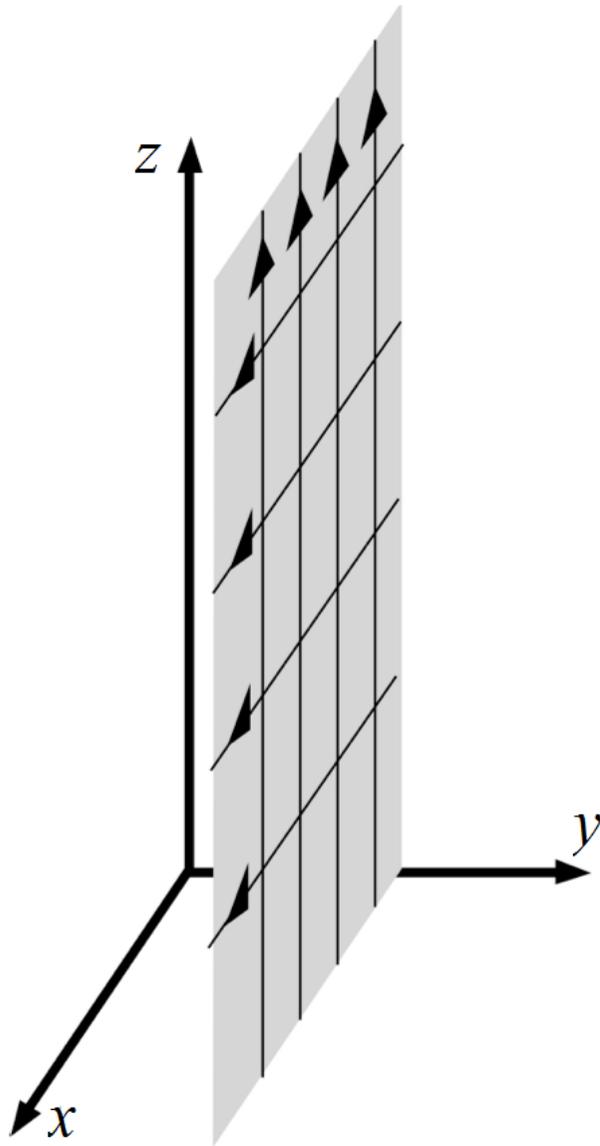
$$j_{E,y} = c \cdot j_{p_y,y}$$

$$E = c \cdot p$$

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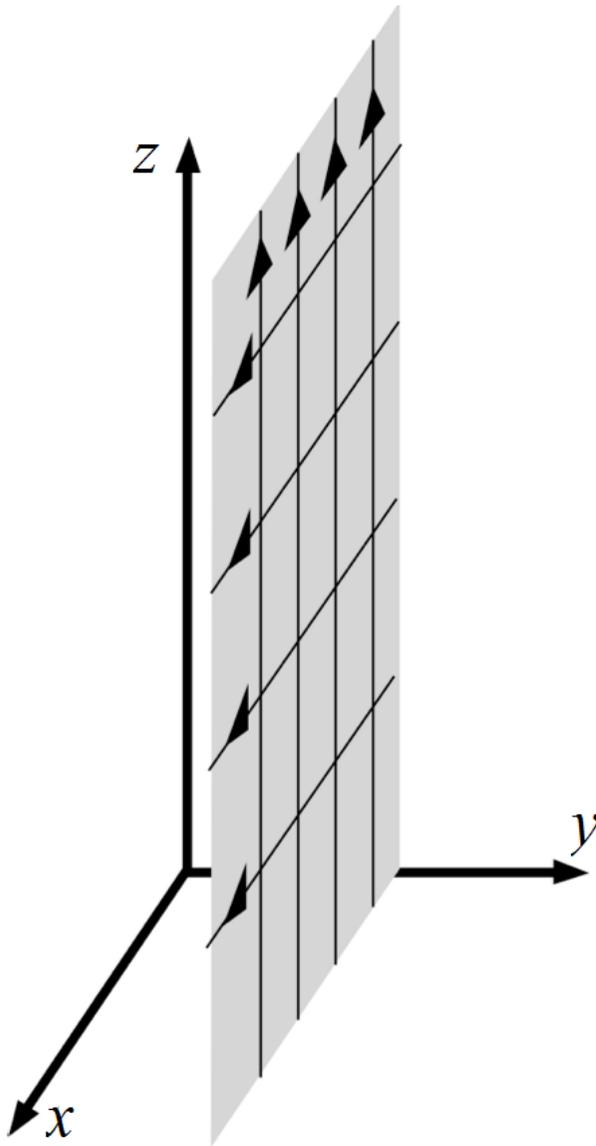
## 4. Light-Version



## 4. Light-Version

el. Feld

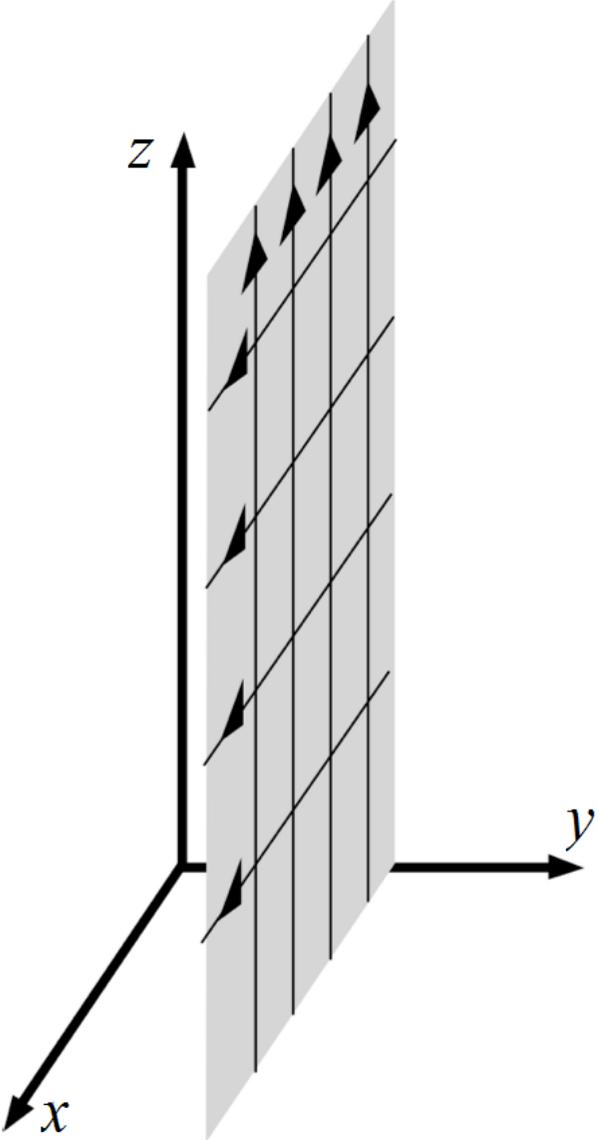
mag. Feld



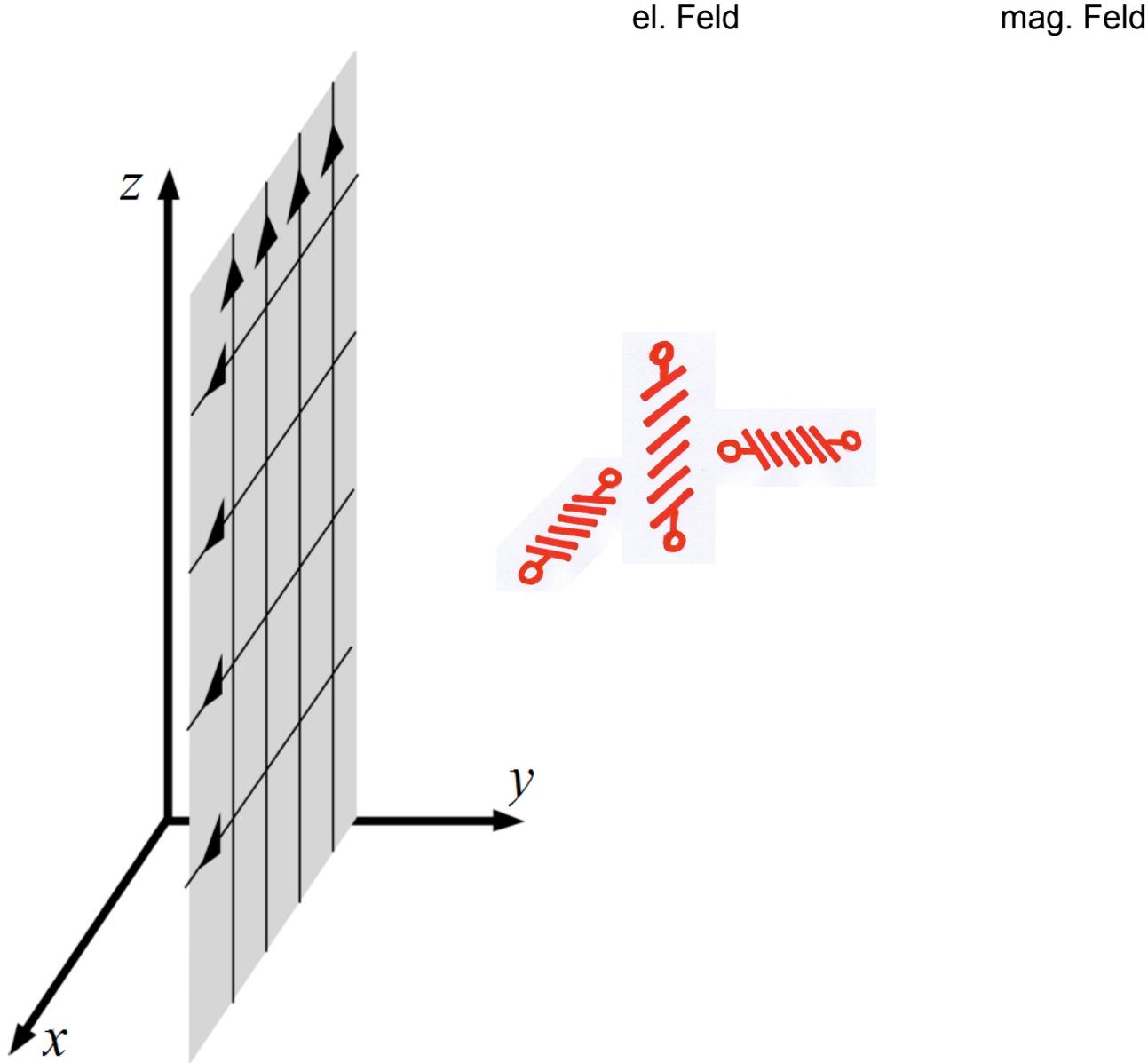
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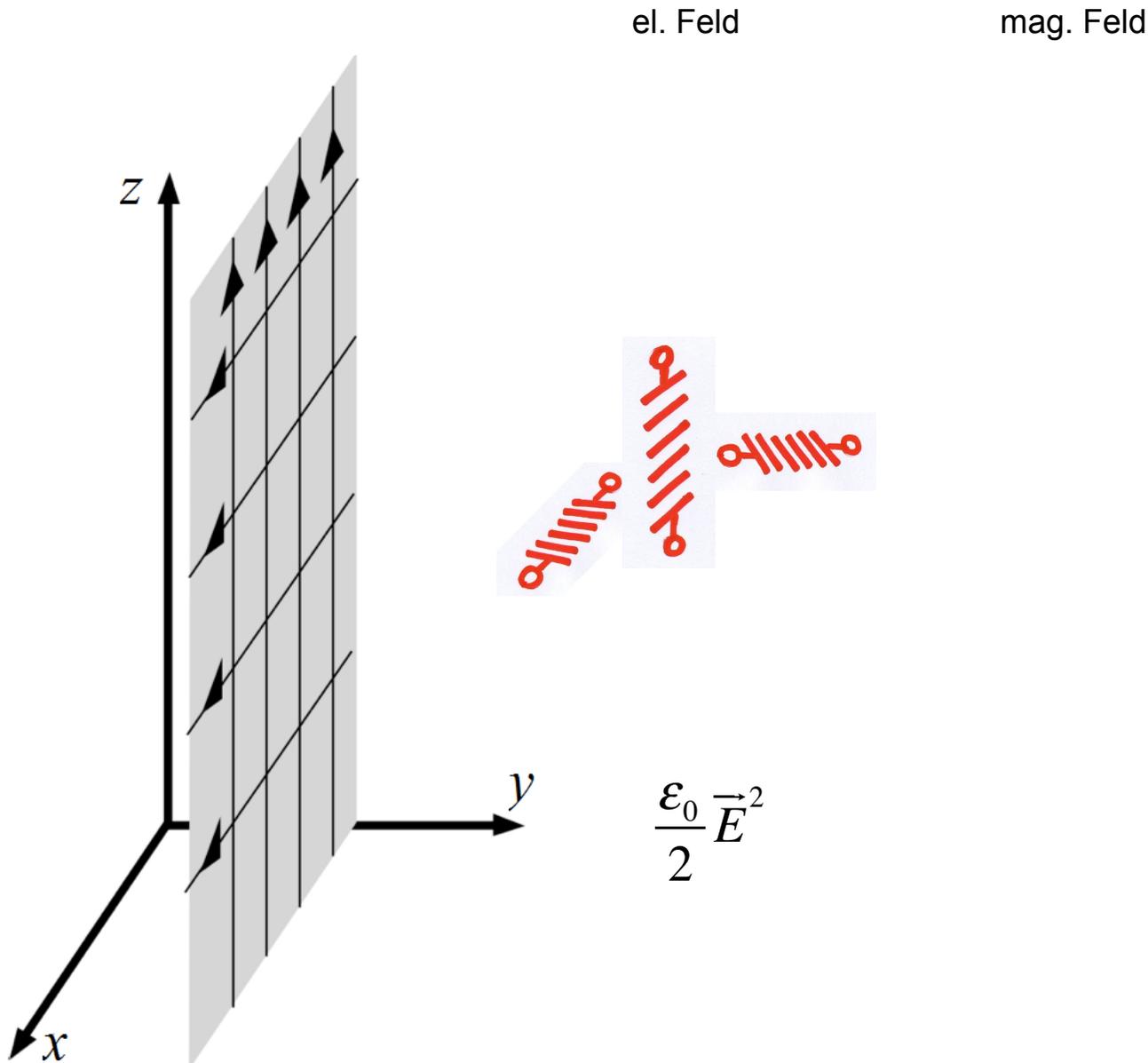
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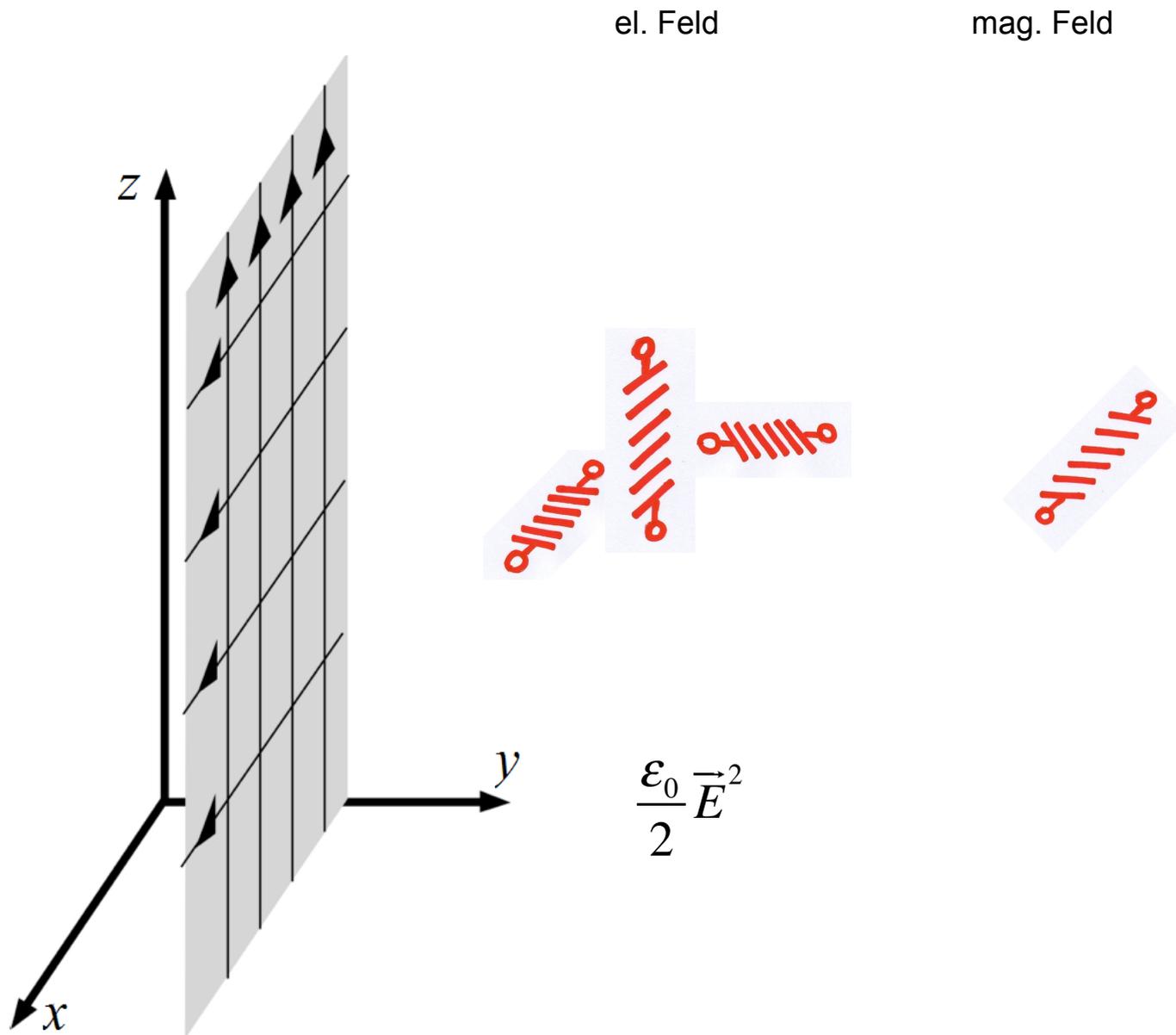
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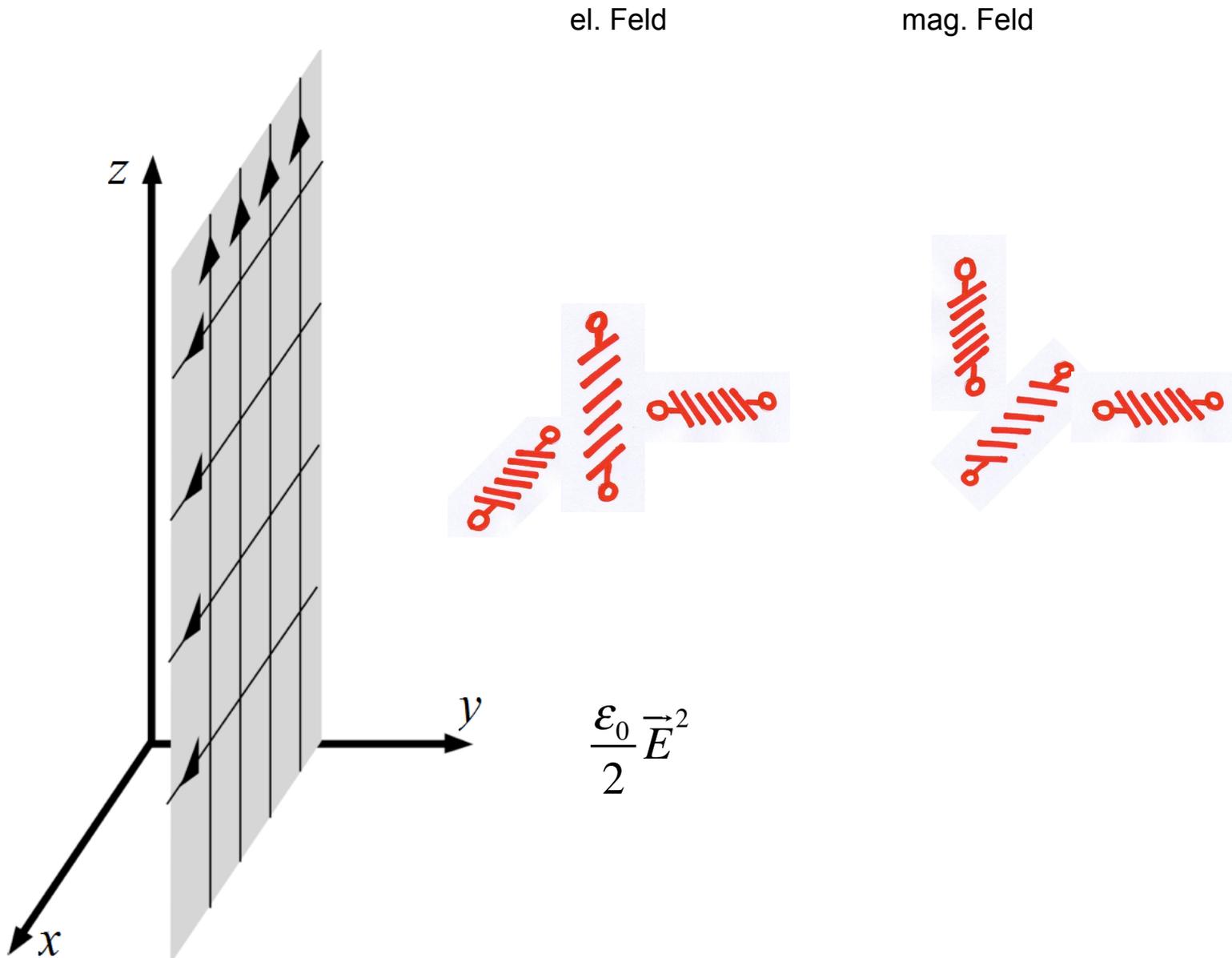
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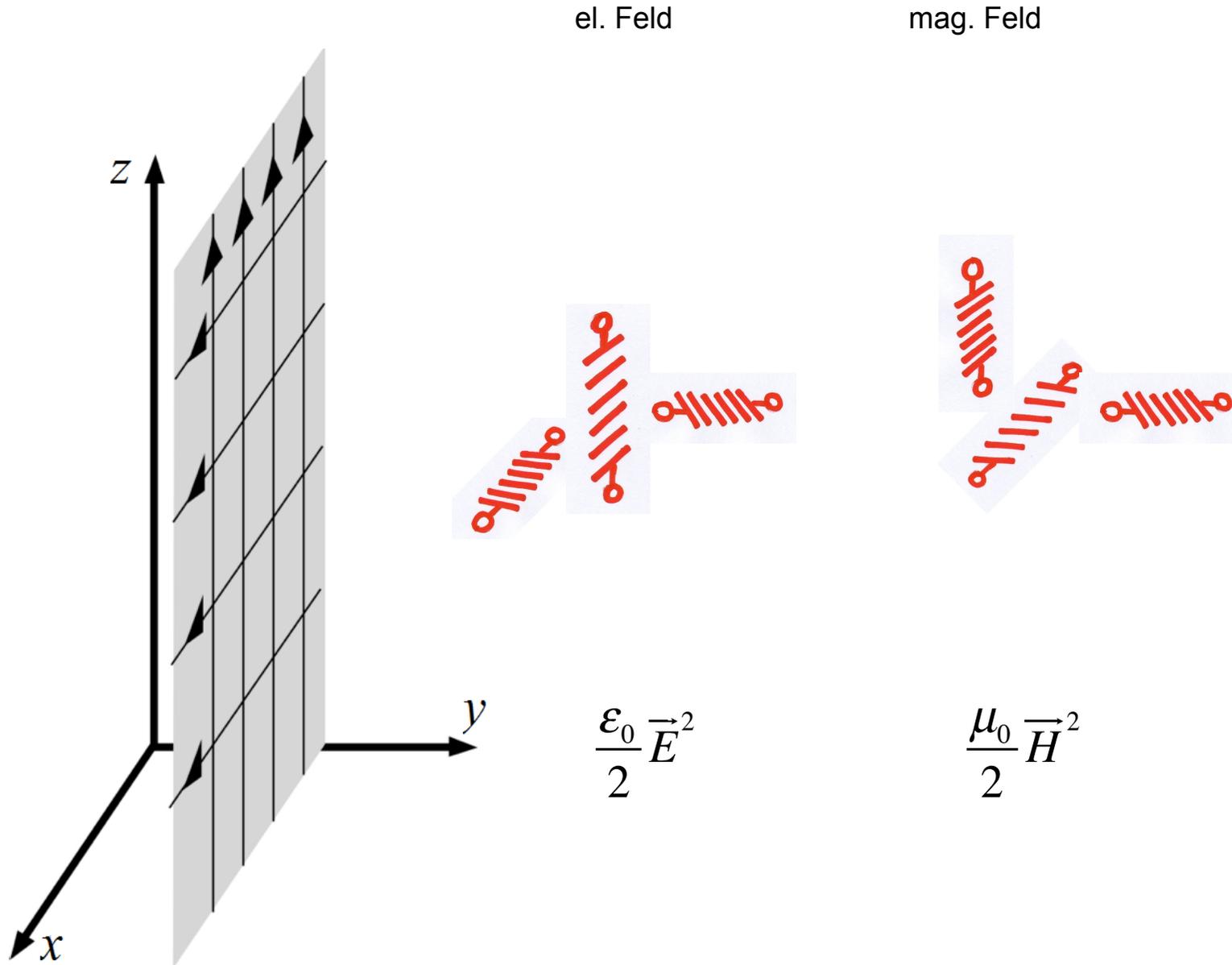
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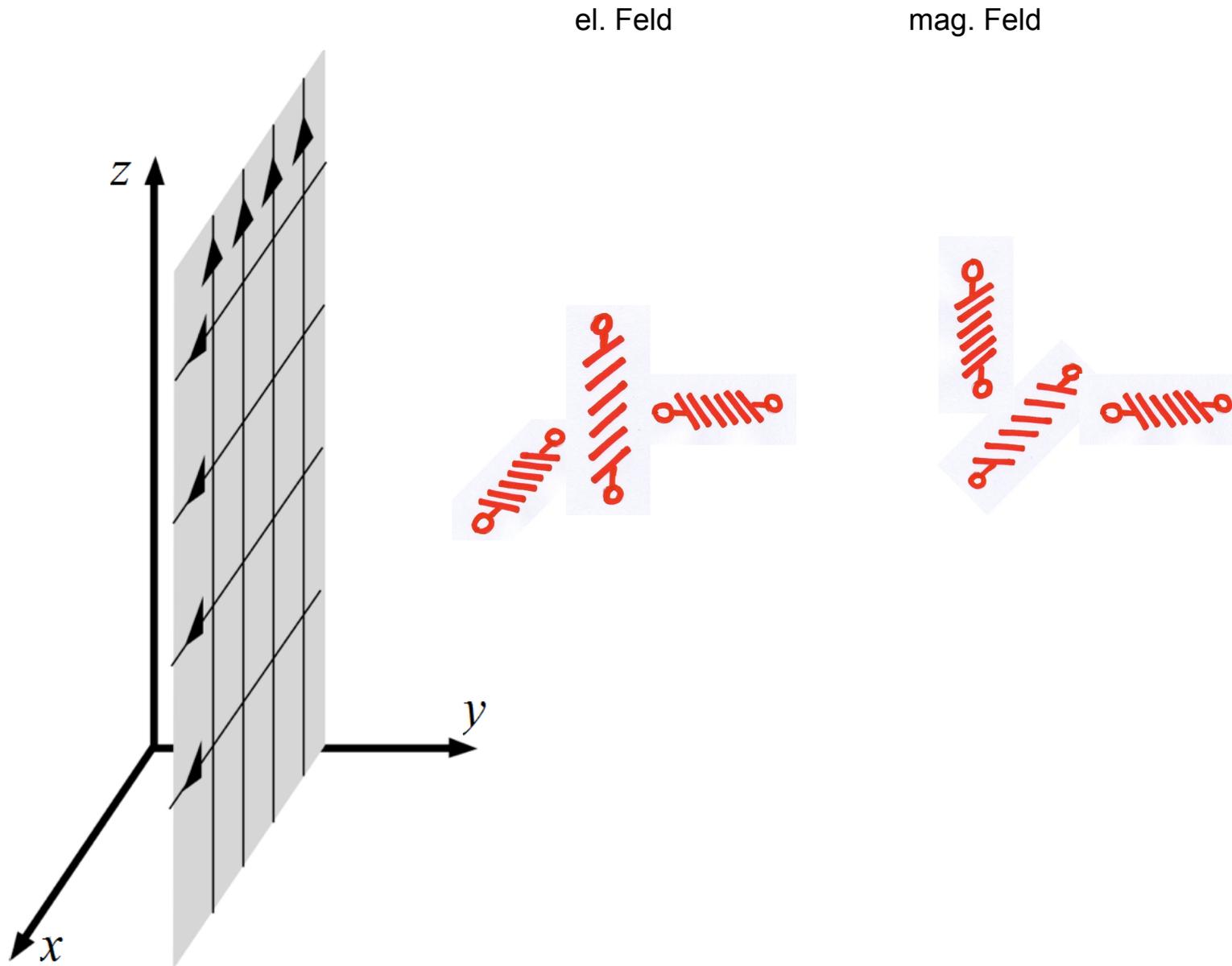
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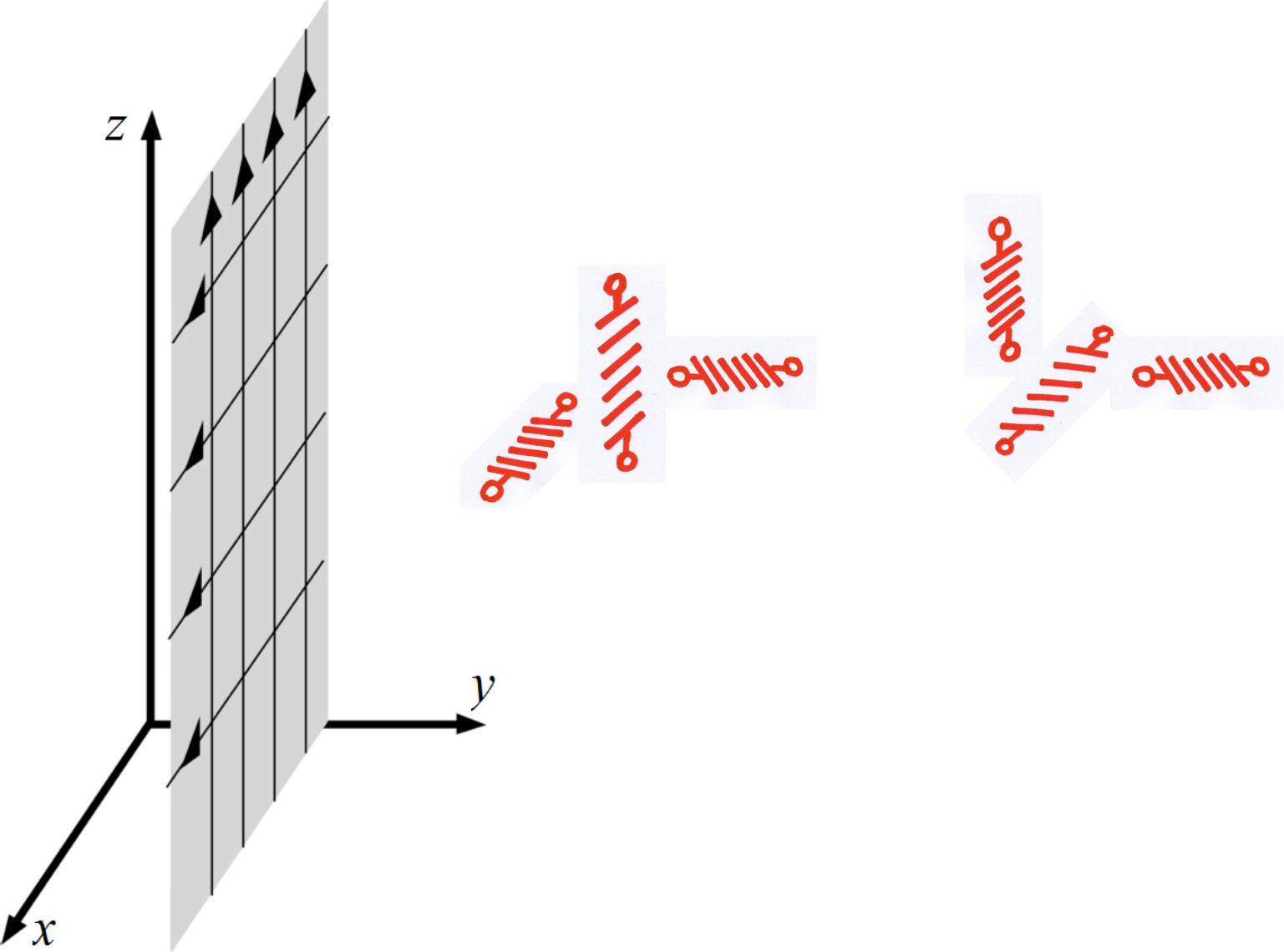


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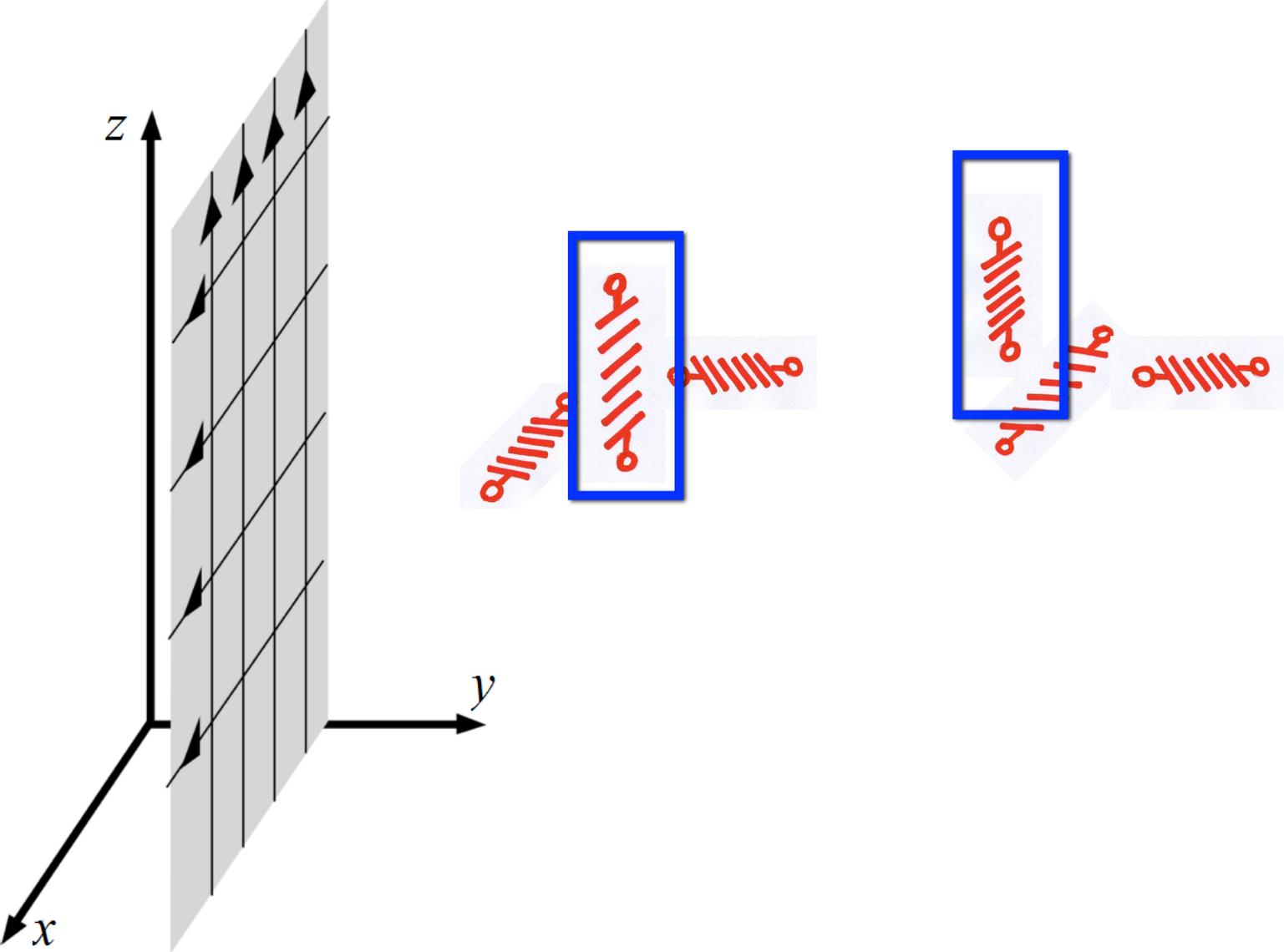
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el.-mag.- Feld



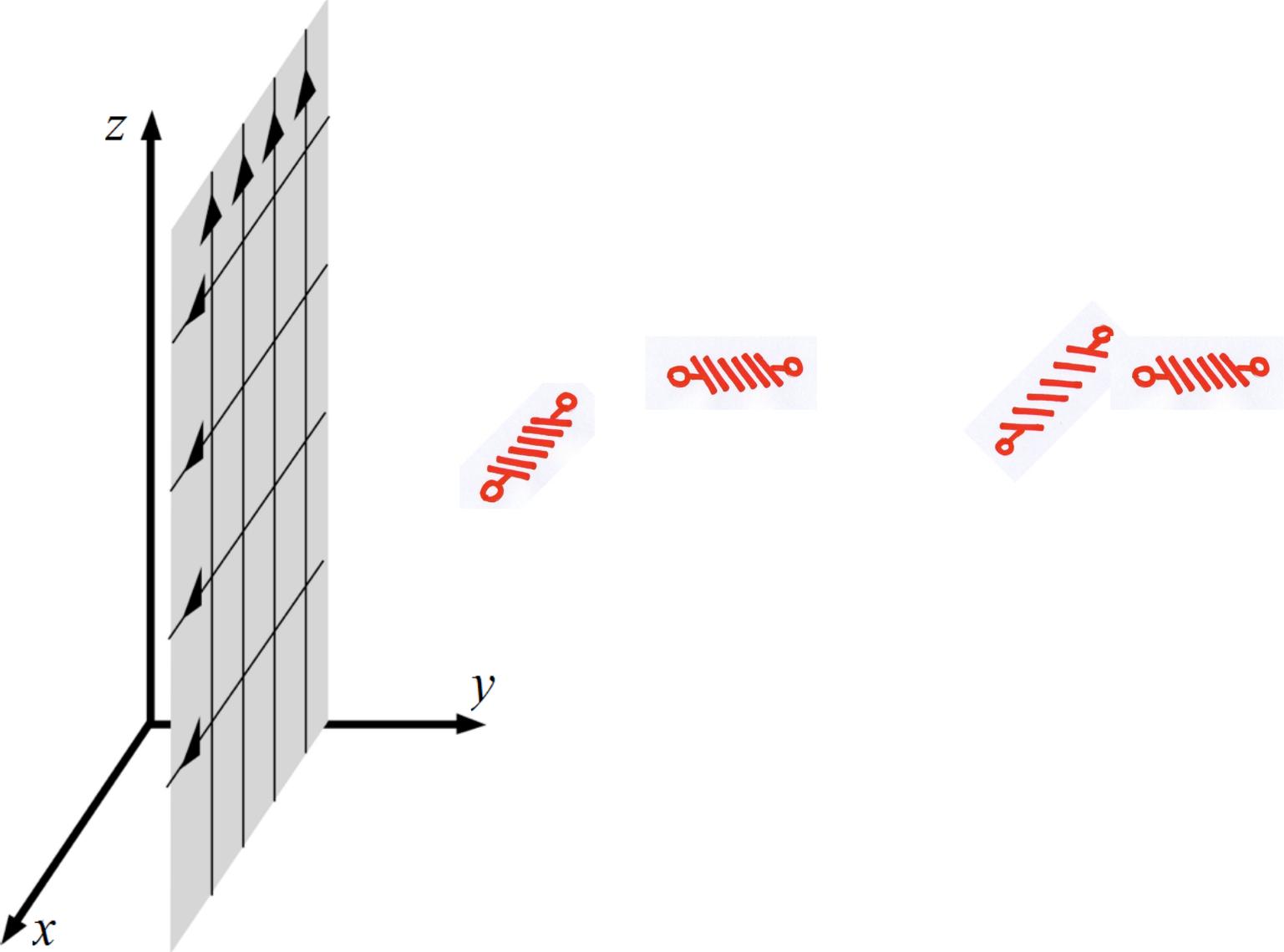
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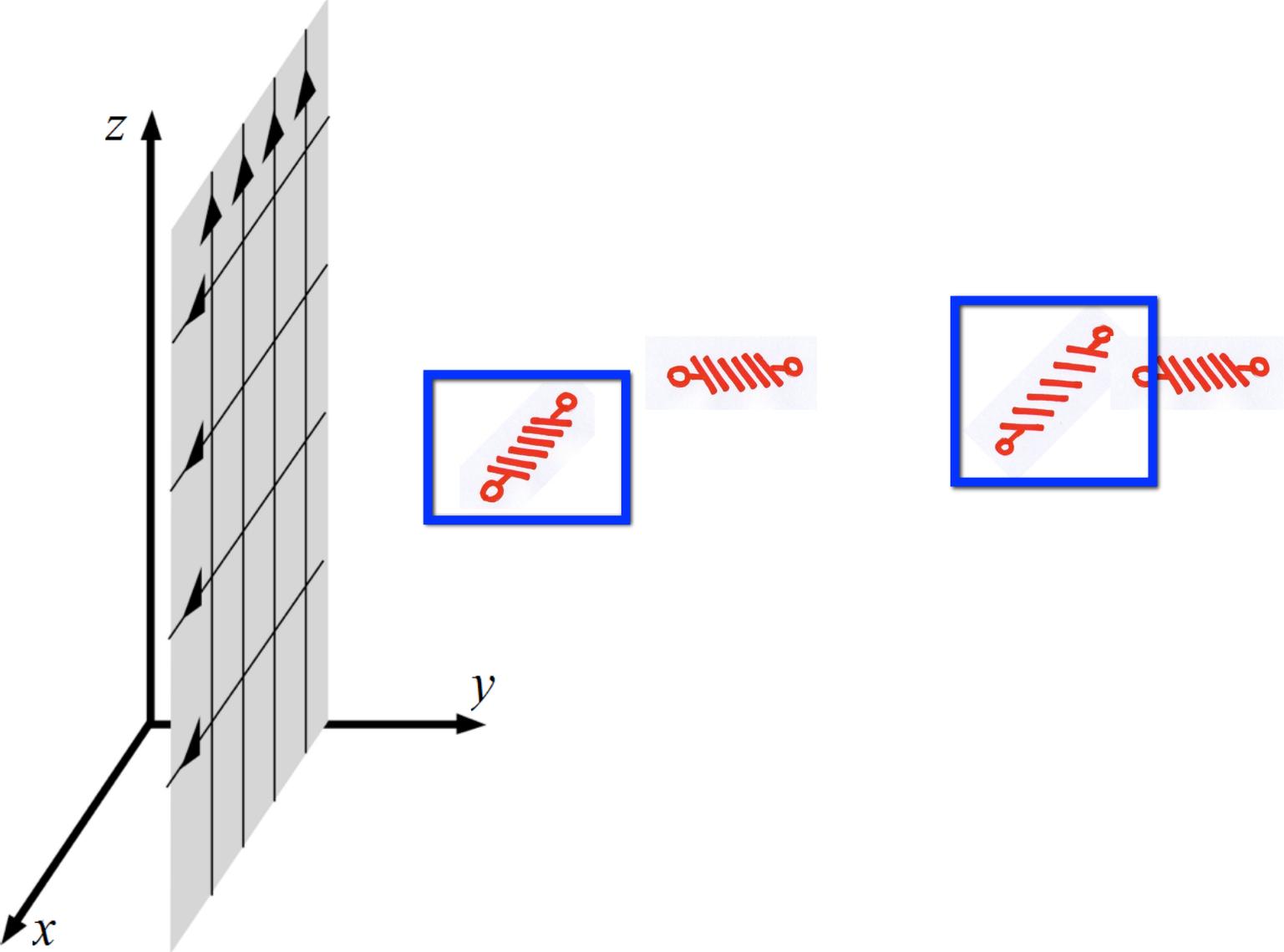
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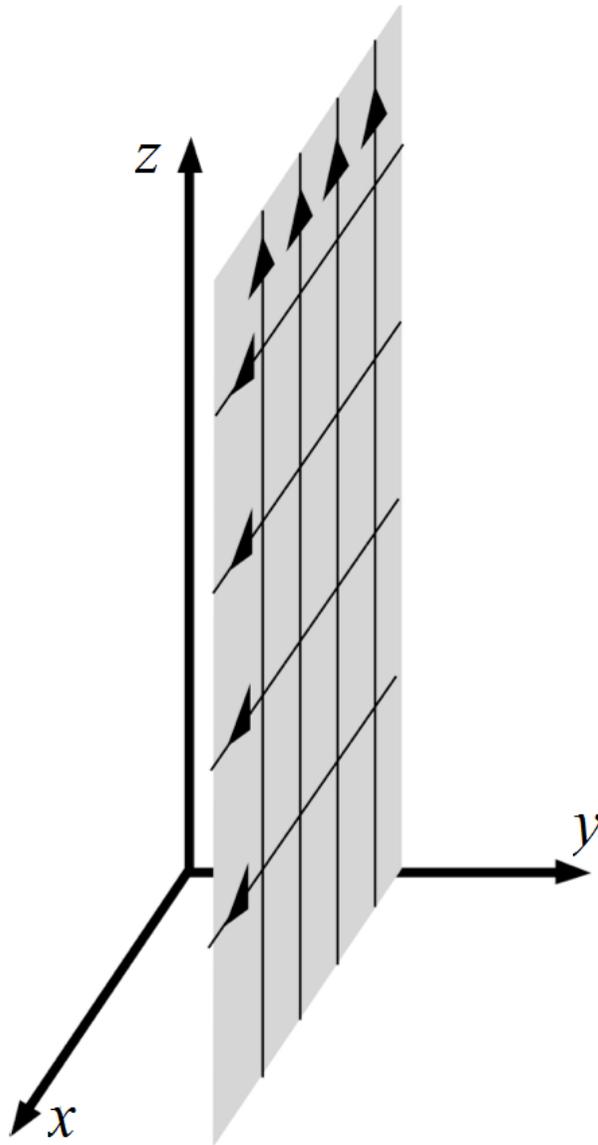
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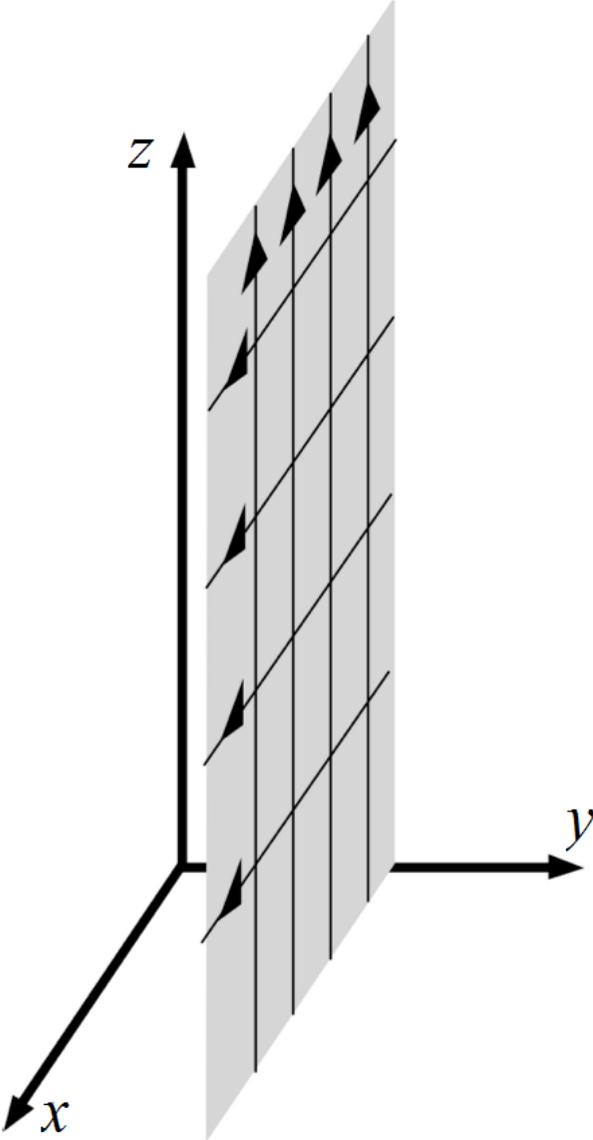
## 4. Light-Version

el.-mag.- Feld



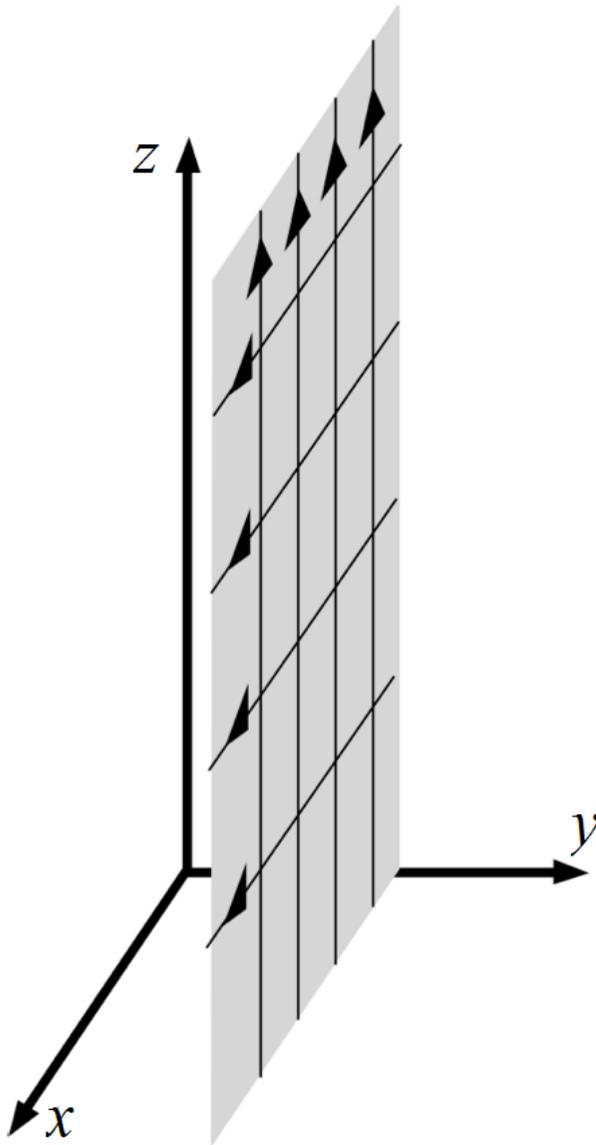
# 4. Light-Version

el.-mag.- Feld



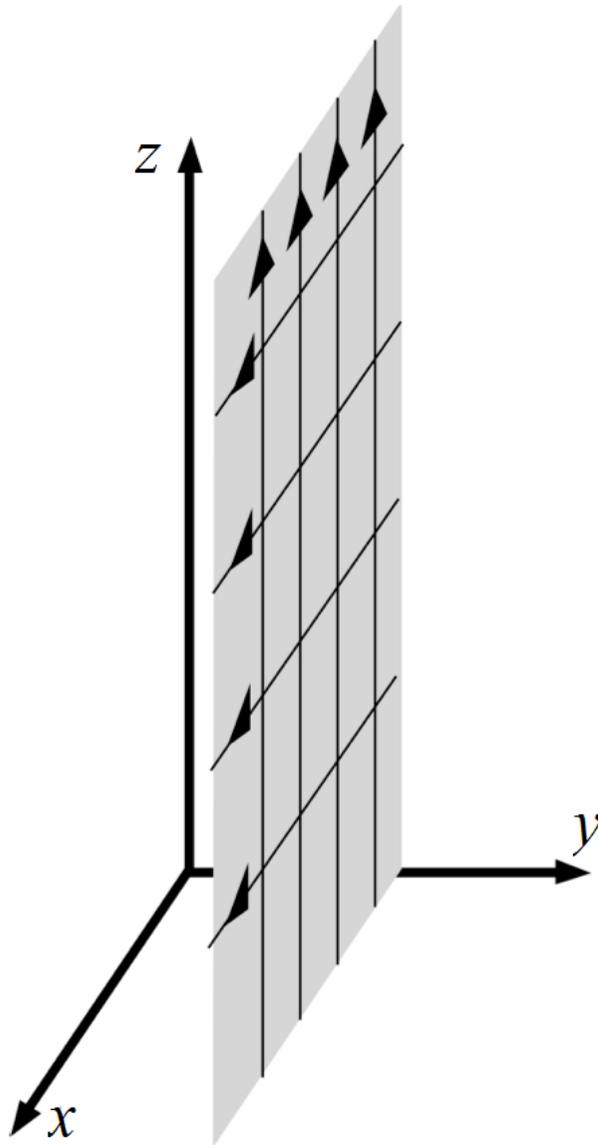
## 4. Light-Version

el.-mag.- Feld



## 4. Light-Version

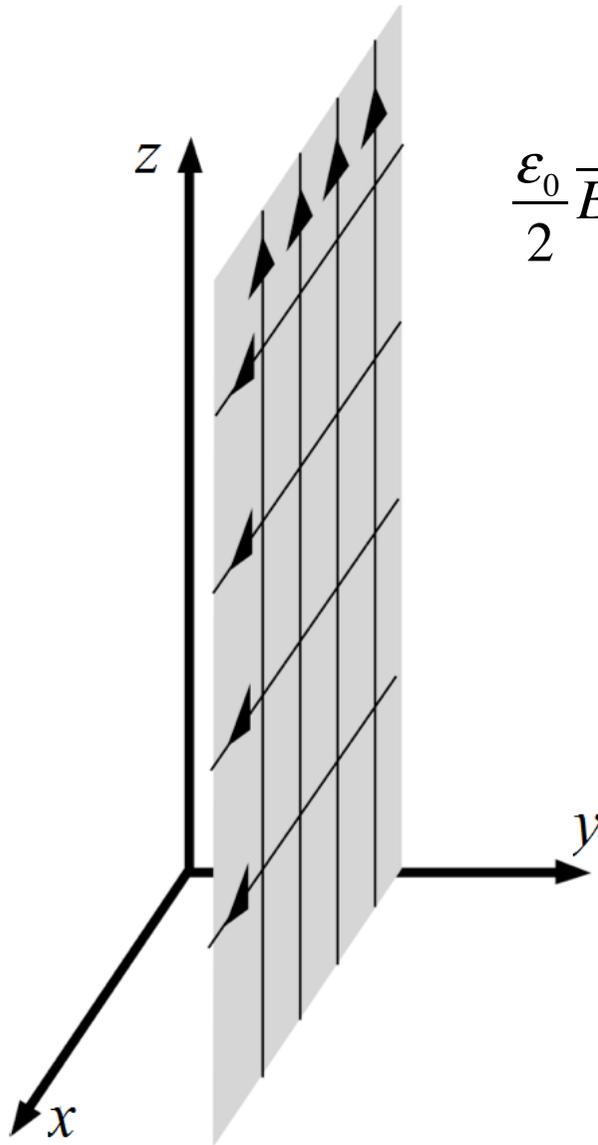
el.-mag.- Feld



Druckspannung in  $y$ -Richtung  
Impuls strömt in der Welle nach rechts

## 4. Light-Version

el.-mag.- Feld

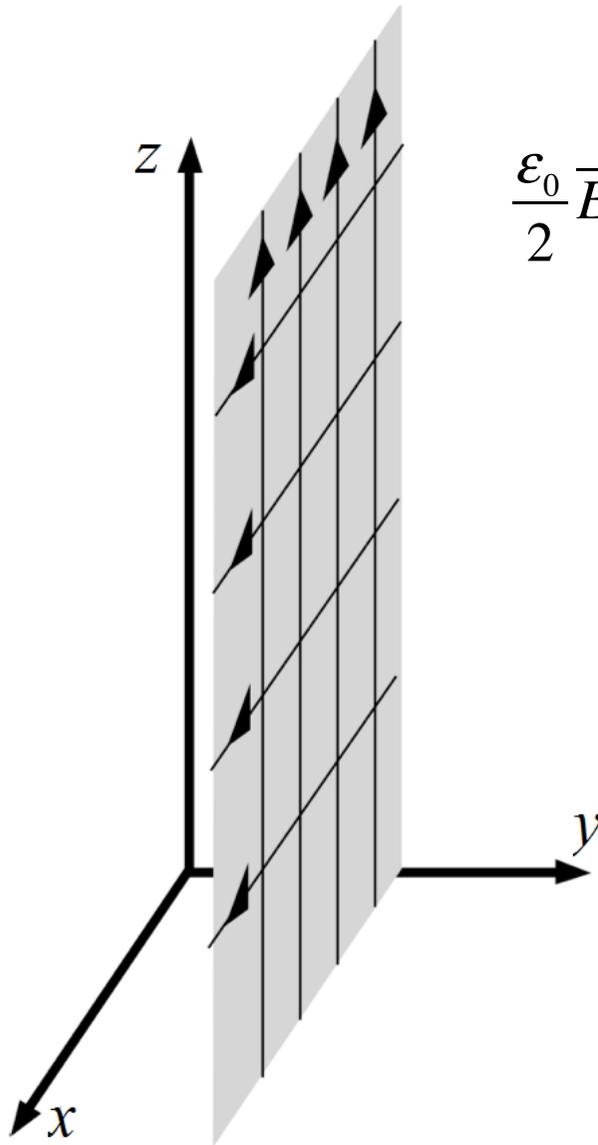


$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = ?$$



## 4. Light-Version

el.-mag.- Feld



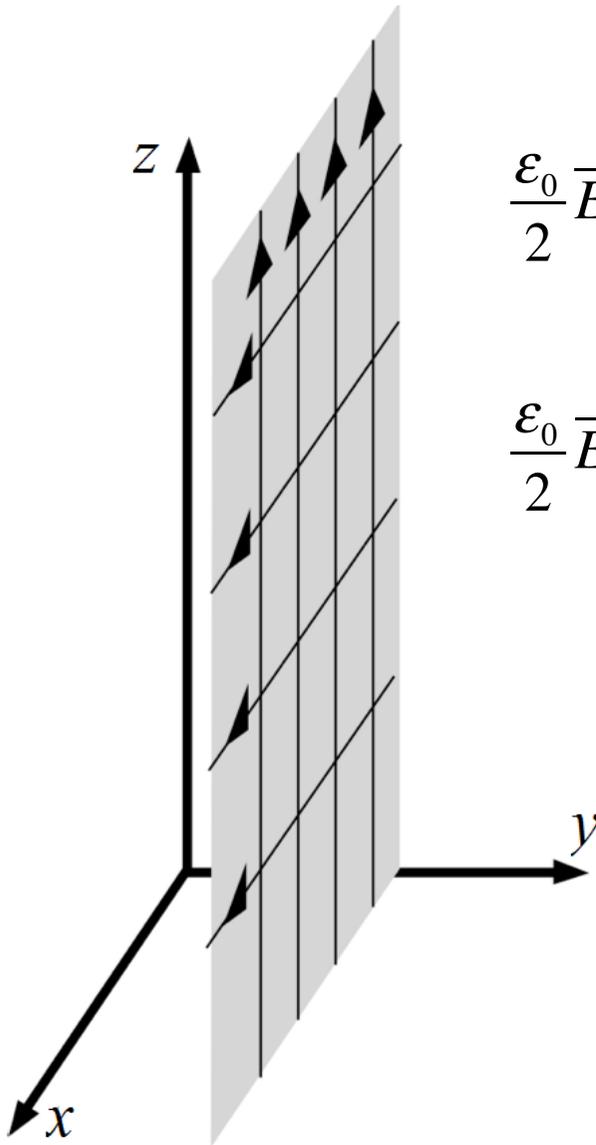
$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = ?$$

$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$



## 4. Light-Version

el.-mag.- Feld



$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = ?$$

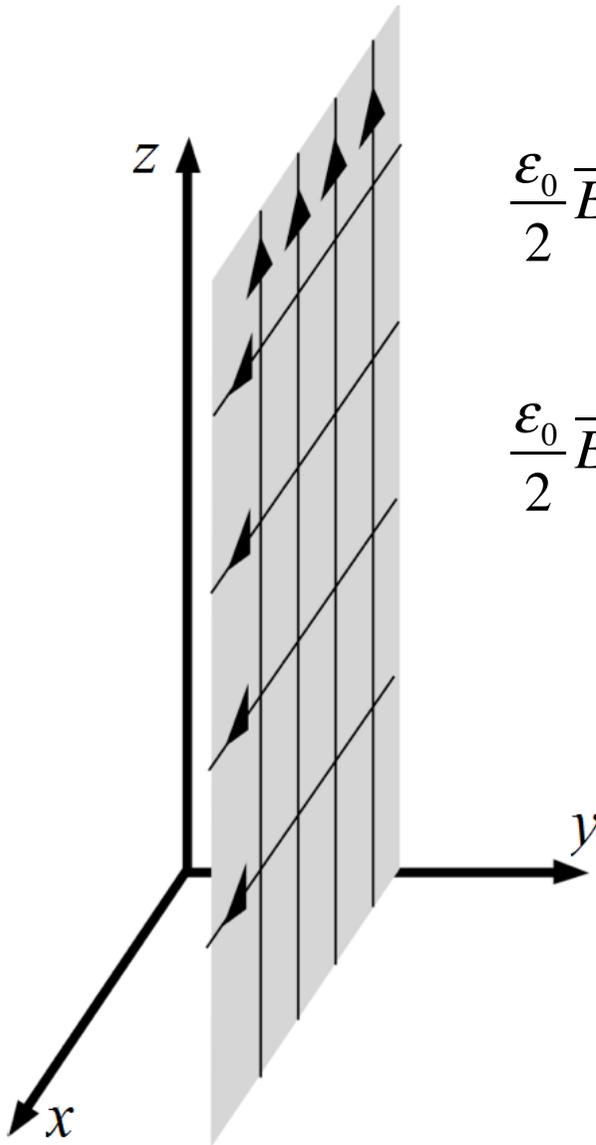
$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$

$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = \epsilon_0 \vec{E}^2 = \mu_0 \vec{H}^2 = \sqrt{\epsilon_0 \mu_0} E_z H_x$$



## 4. Light-Version

el.-mag.- Feld



$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = ?$$

$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$

$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = \epsilon_0 \vec{E}^2 = \mu_0 \vec{H}^2 = \sqrt{\epsilon_0 \mu_0} E_z H_x$$

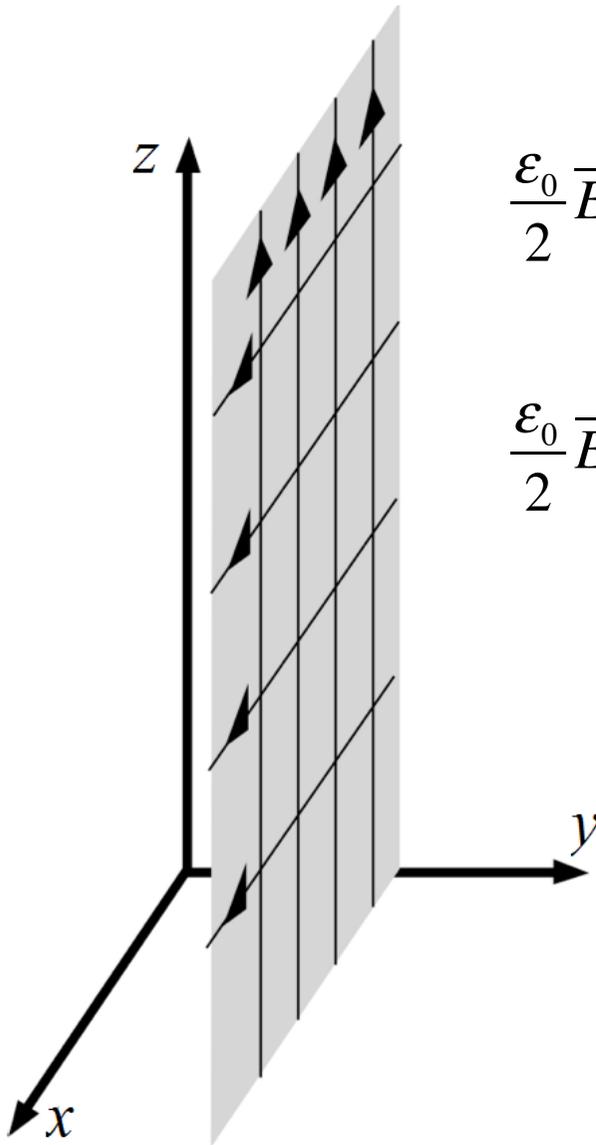


$$j_{p_{y,y}} = \sqrt{\epsilon_0 \mu_0} E_z H_x$$

$$j_{E,y} = E_z H_x$$

## 4. Light-Version

el.-mag.- Feld



$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = ?$$

$$\frac{\epsilon_0}{2} \vec{E}^2 = \frac{\mu_0}{2} \vec{H}^2$$

$$\frac{\epsilon_0}{2} \vec{E}^2 + \frac{\mu_0}{2} \vec{H}^2 = \epsilon_0 \vec{E}^2 = \mu_0 \vec{H}^2 = \sqrt{\epsilon_0 \mu_0} E_z H_x$$

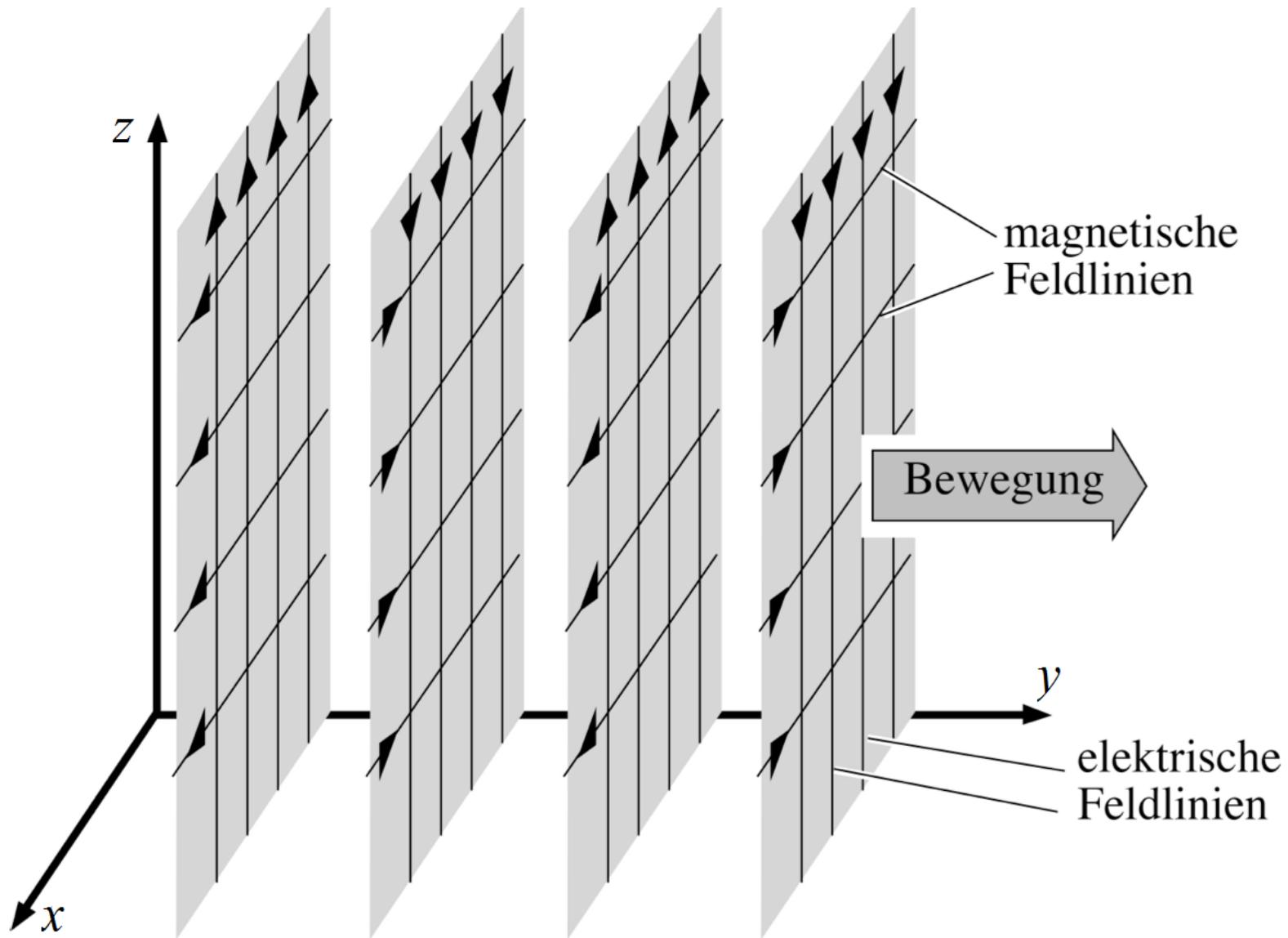


$$j_{p_{y,y}} = \sqrt{\epsilon_0 \mu_0} E_z H_x$$

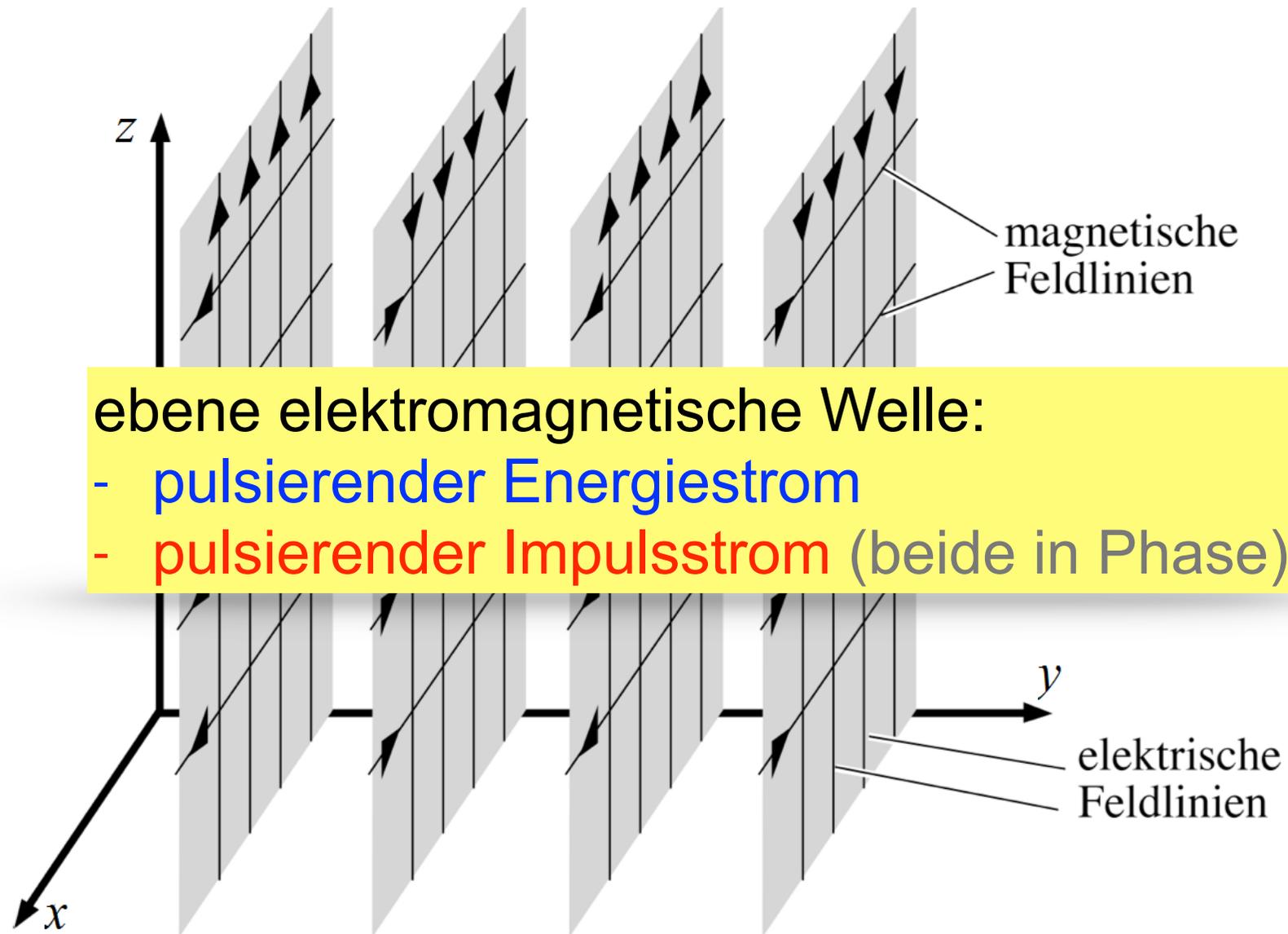
$$j_{E,y} = E_z H_x$$

$$j_E = \frac{1}{\sqrt{\epsilon_0 \mu_0}} j_{p_y} = c \cdot j_{p_y}$$

## 4. Light-Version



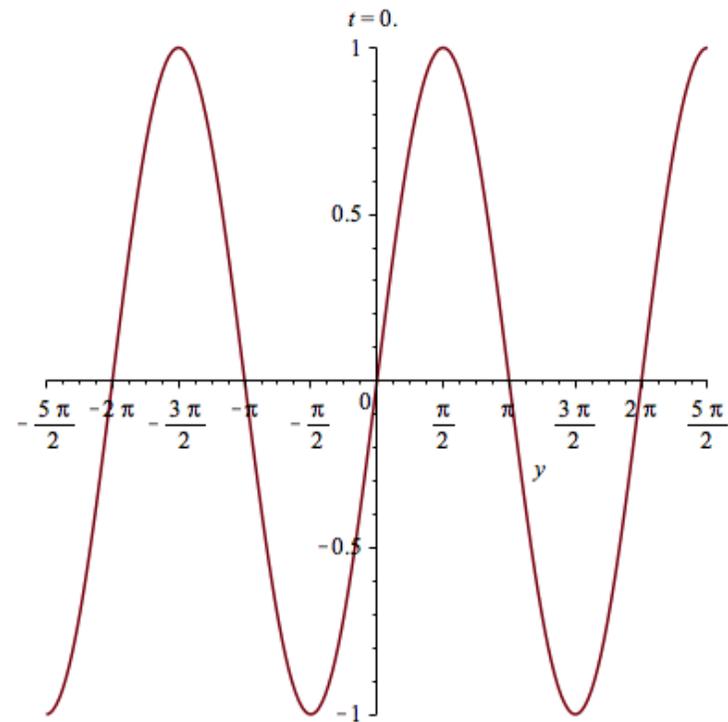
## 4. Light-Version



A Elektromagnetische Welle

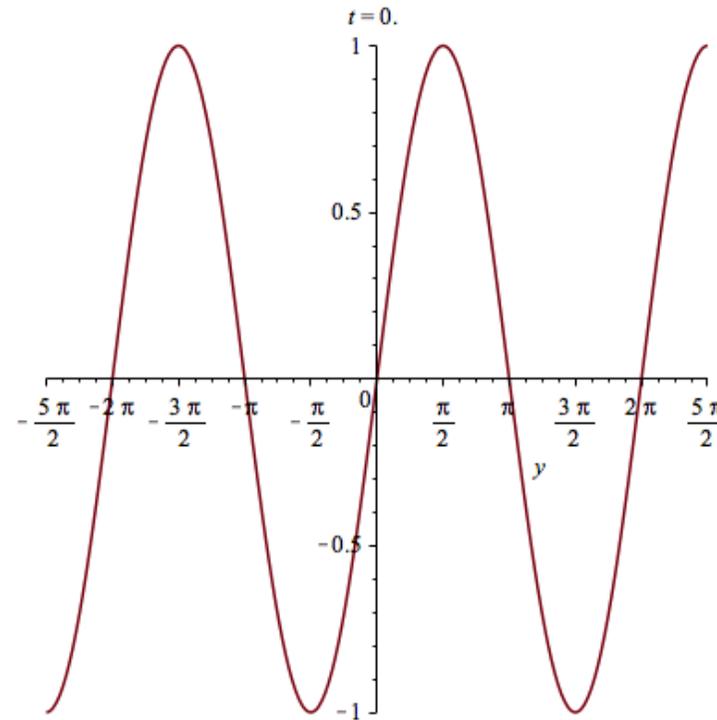
B stehende elektromagnetische Welle

# B stehende elektromagnetische Welle



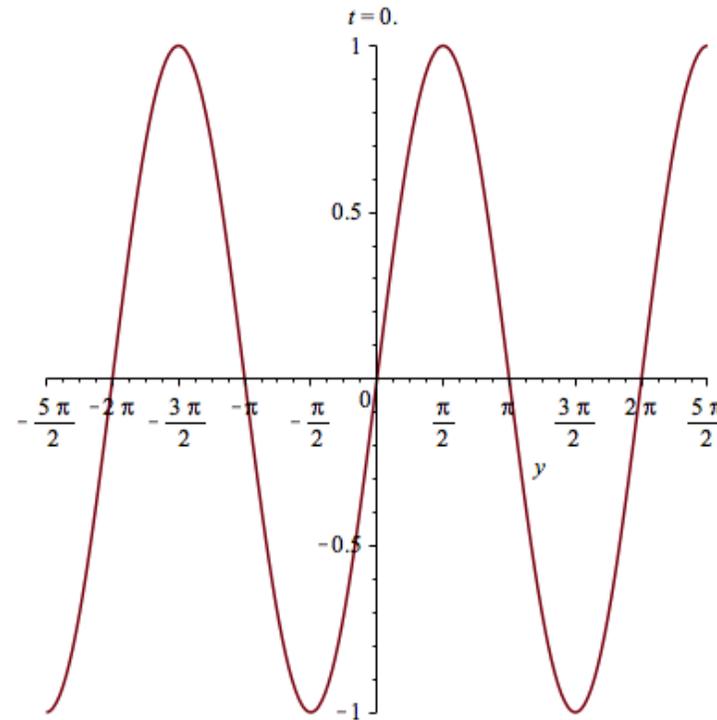
# B stehende elektromagnetische Welle

Welle nach rechts



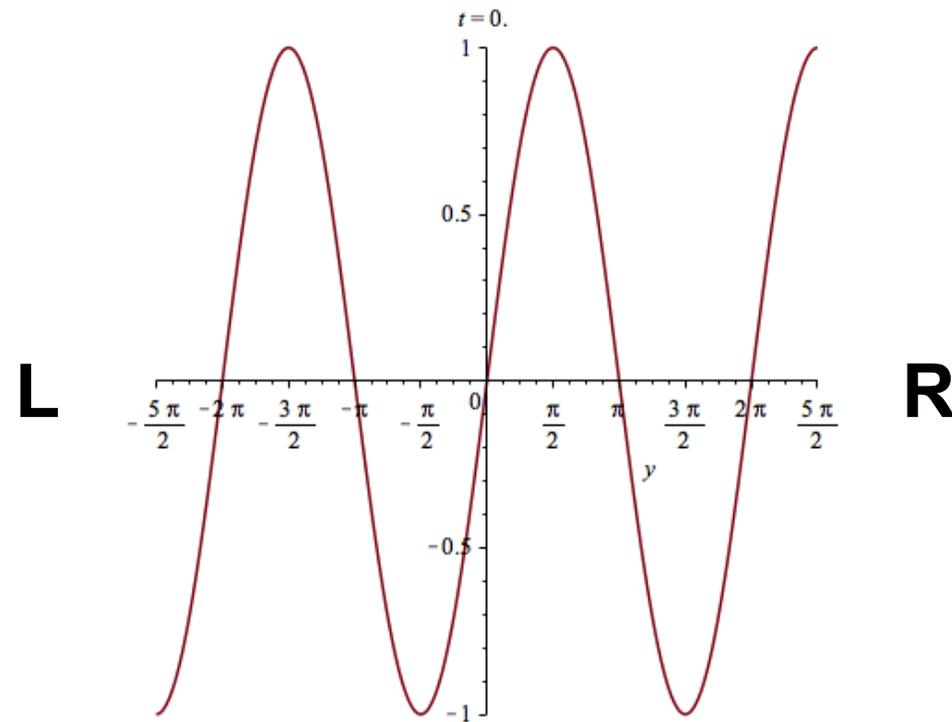
# B stehende elektromagnetische Welle

Welle nach rechts



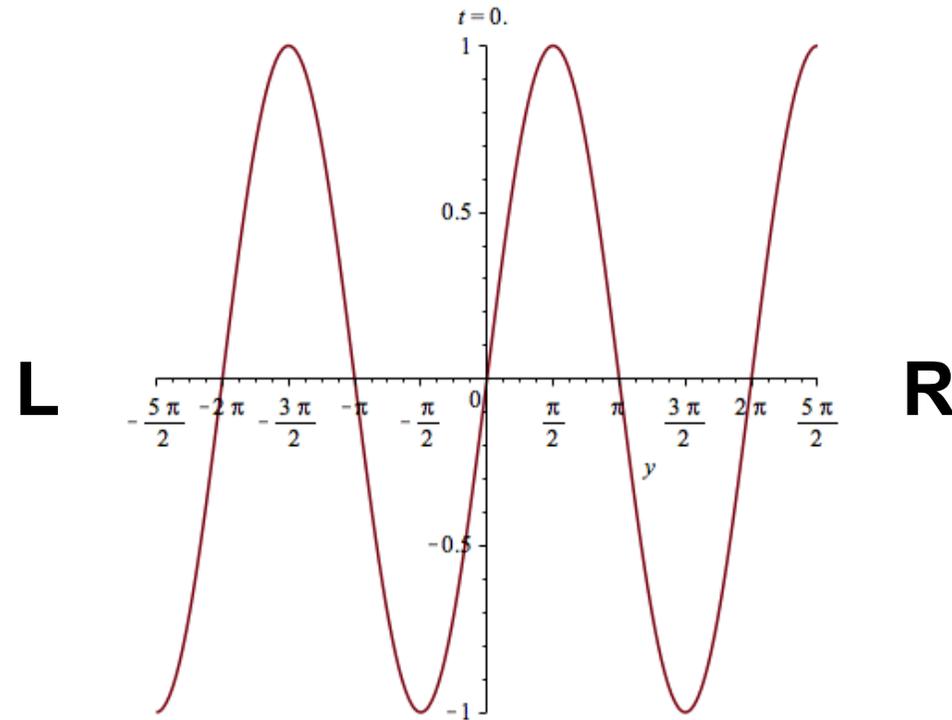
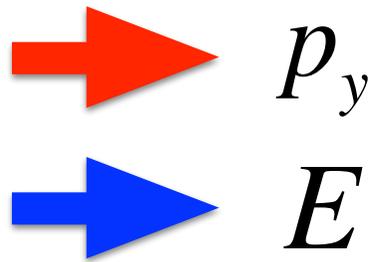
# B stehende elektromagnetische Welle

Welle nach rechts



# B stehende elektromagnetische Welle

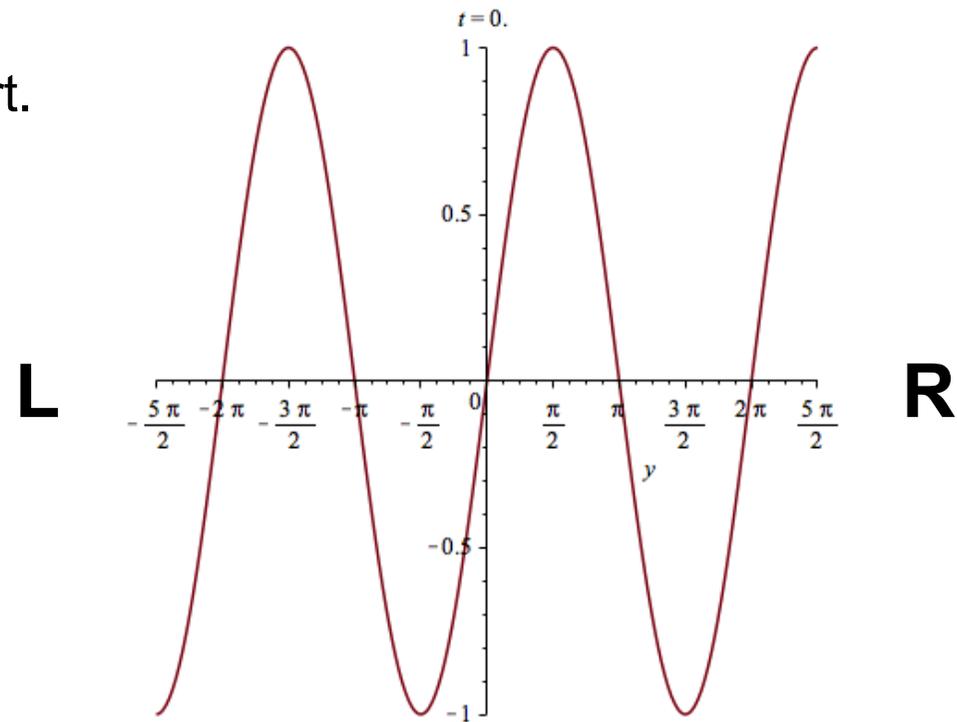
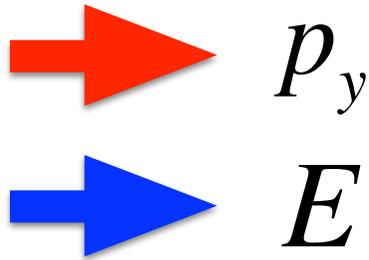
Welle nach rechts



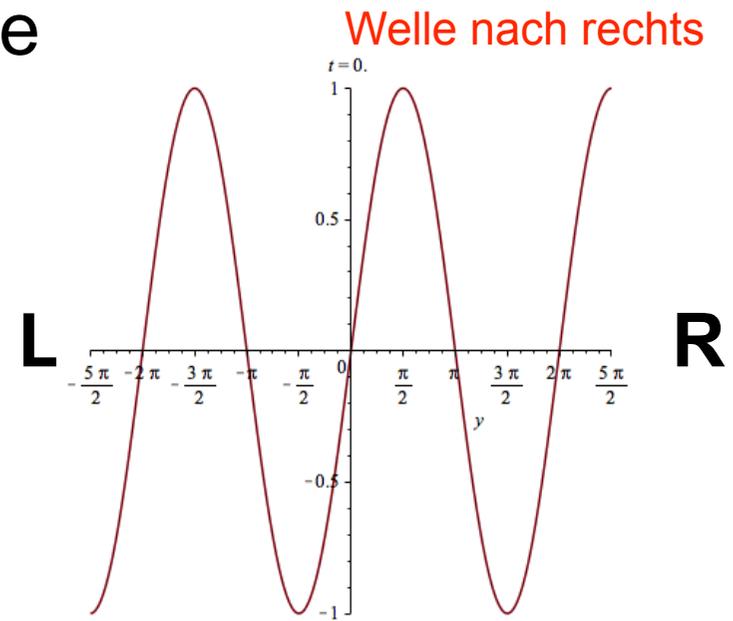
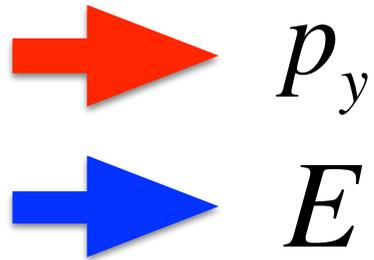
# B stehende elektromagnetische Welle

Welle nach rechts

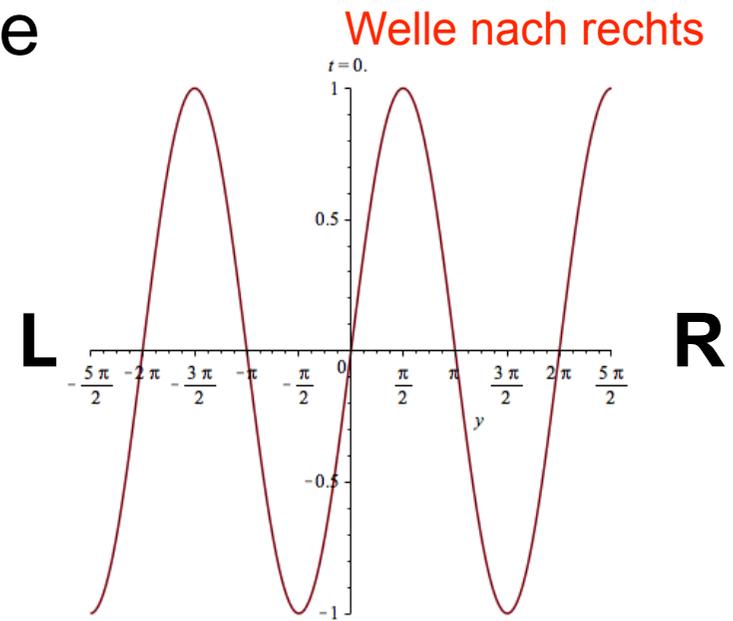
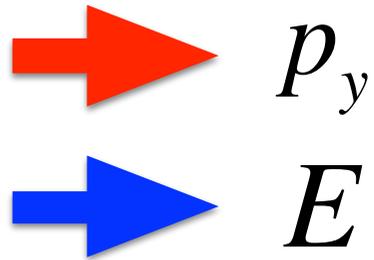
Energie und (positiver) Impuls werden von **L** nach **R** transportiert.



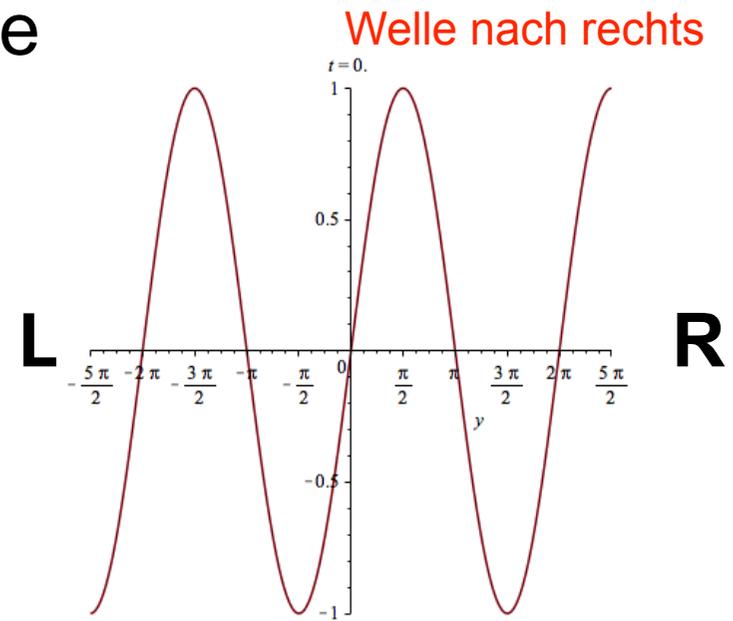
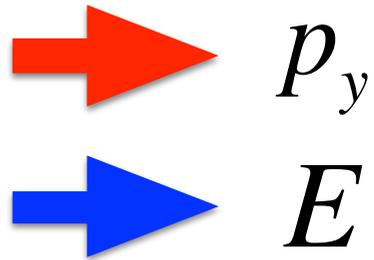
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle

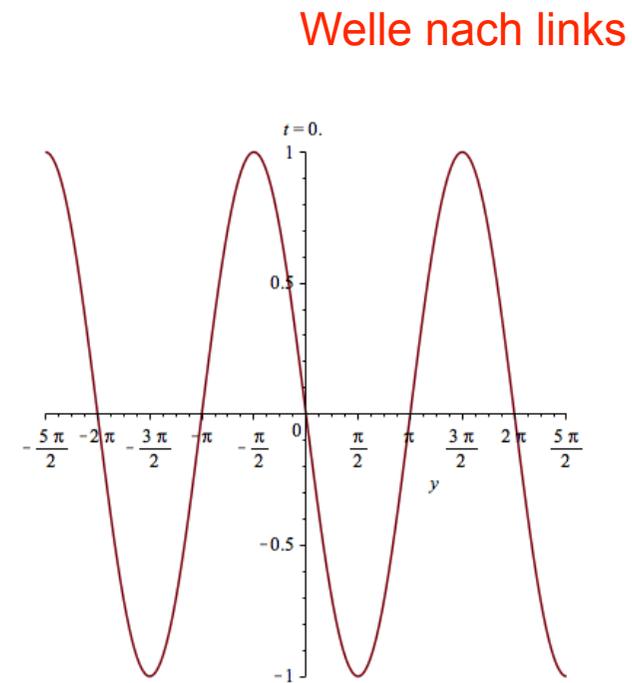
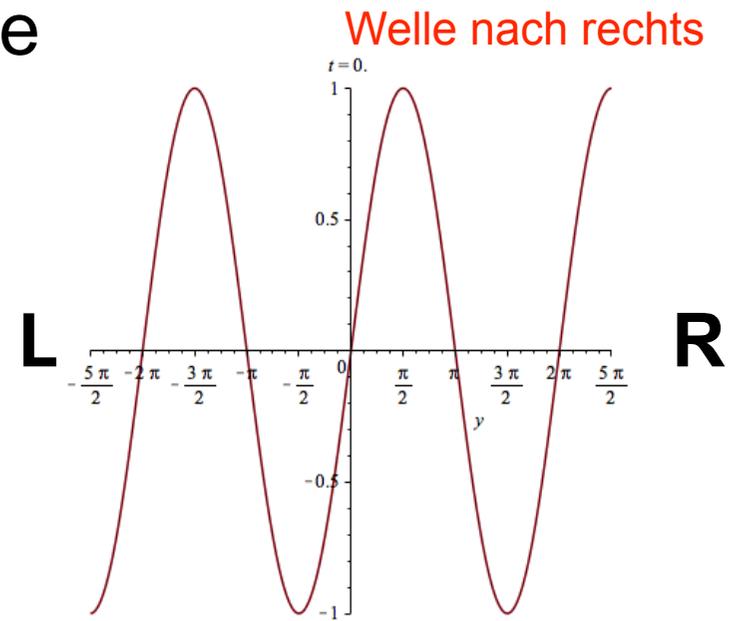
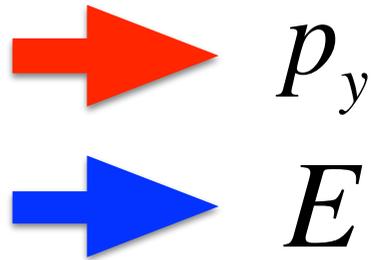


# B stehende elektromagnetische Welle

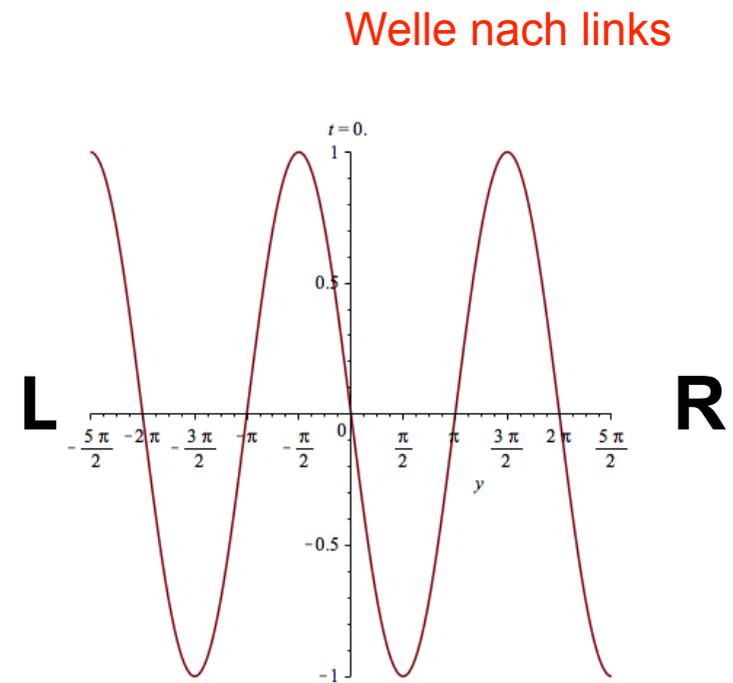
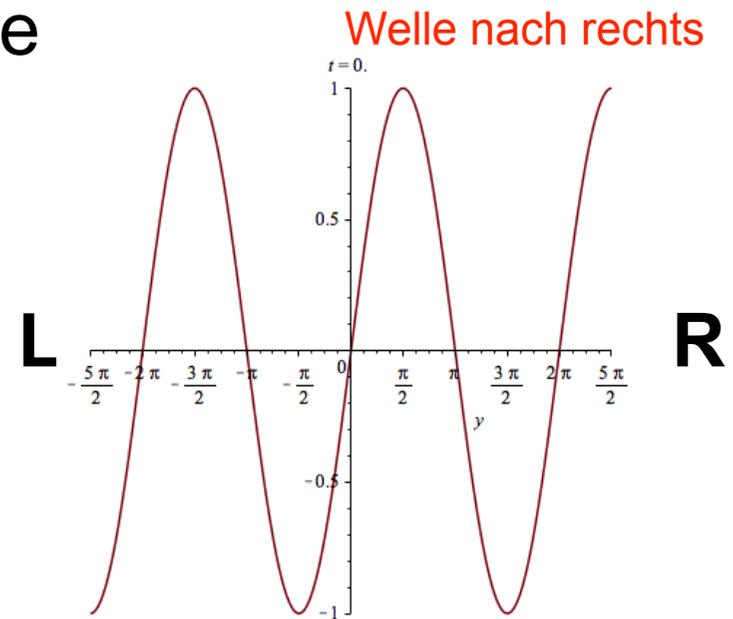
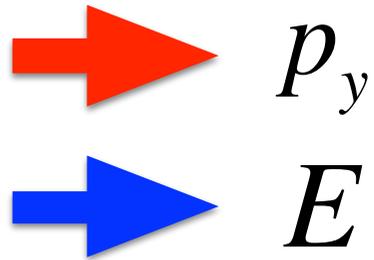


Welle nach links

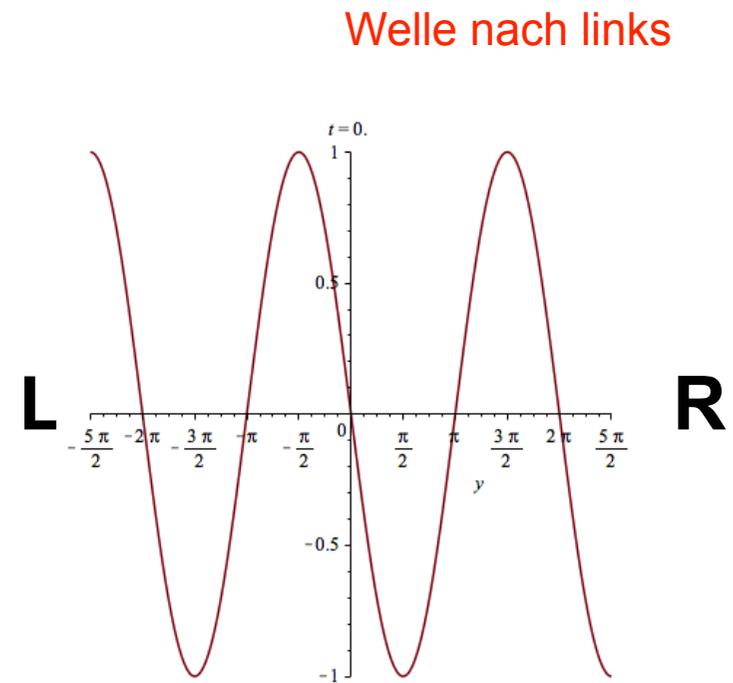
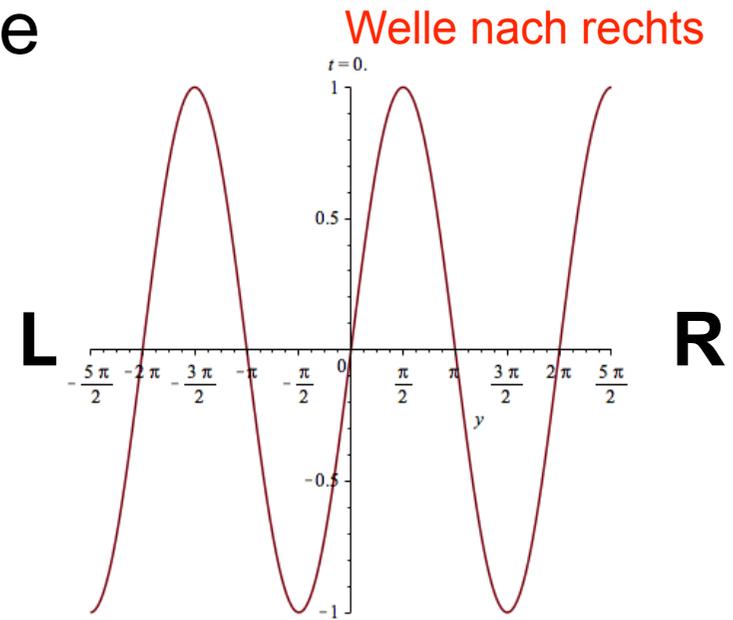
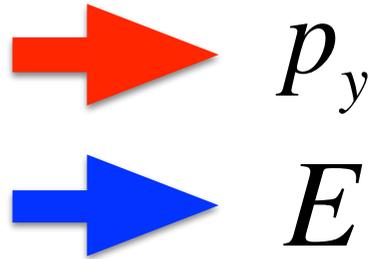
# B stehende elektromagnetische Welle



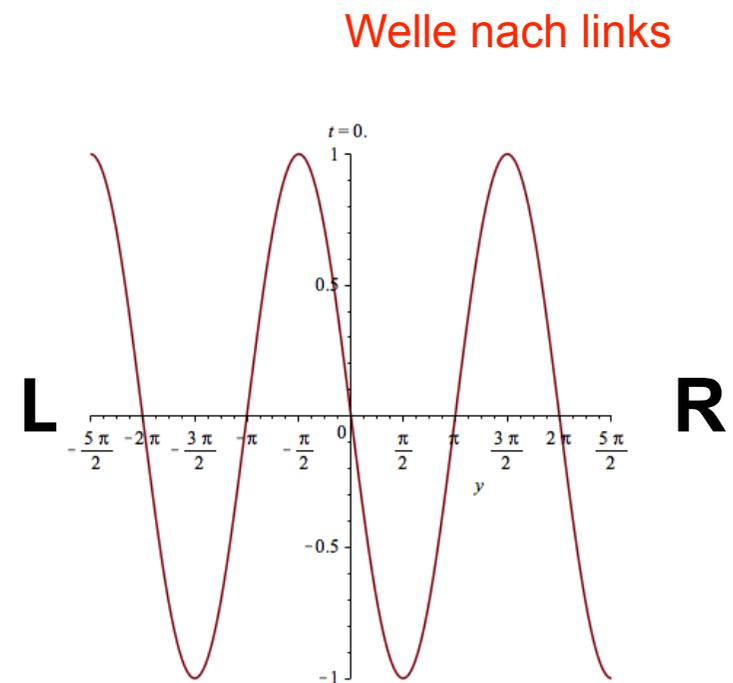
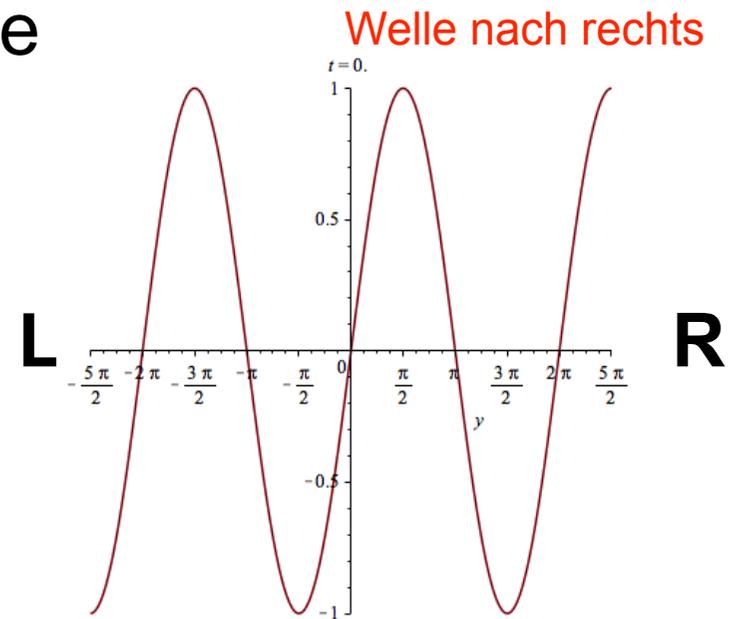
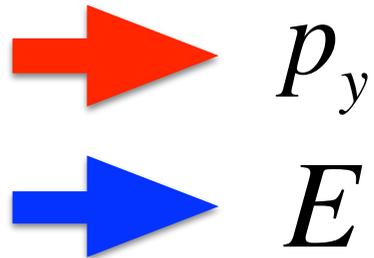
# B stehende elektromagnetische Welle



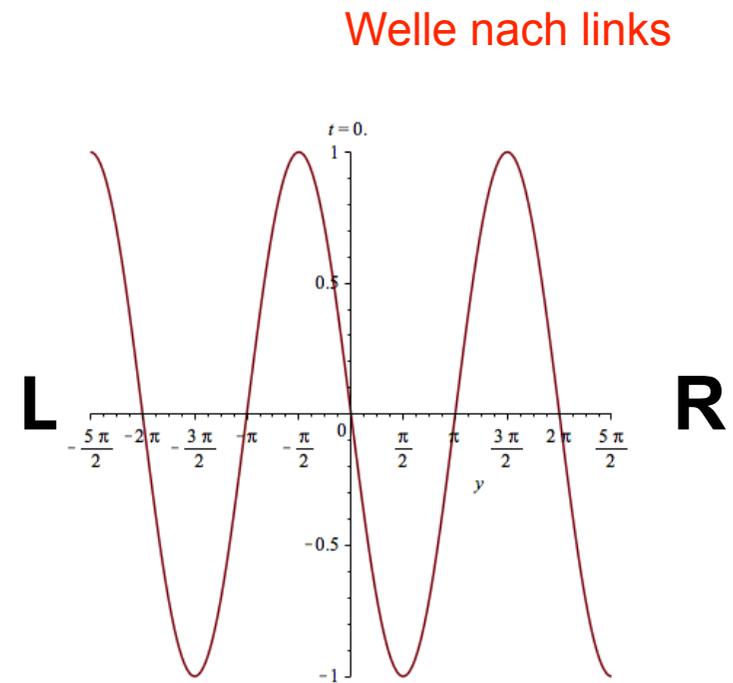
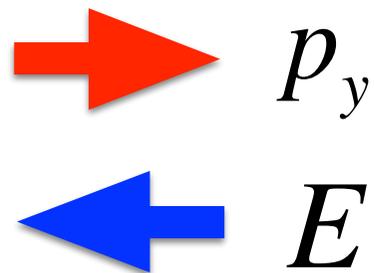
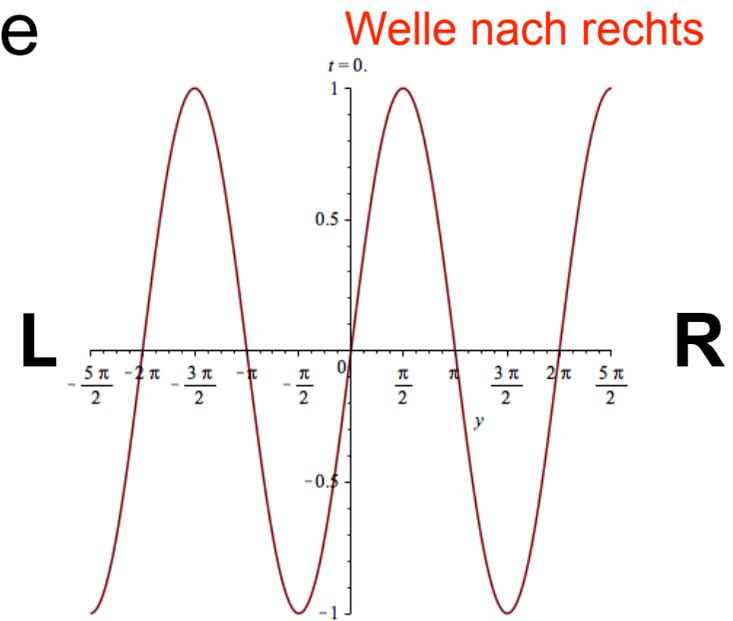
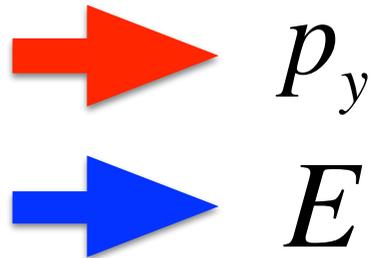
# B stehende elektromagnetische Welle



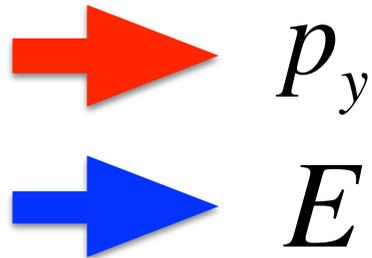
# B stehende elektromagnetische Welle



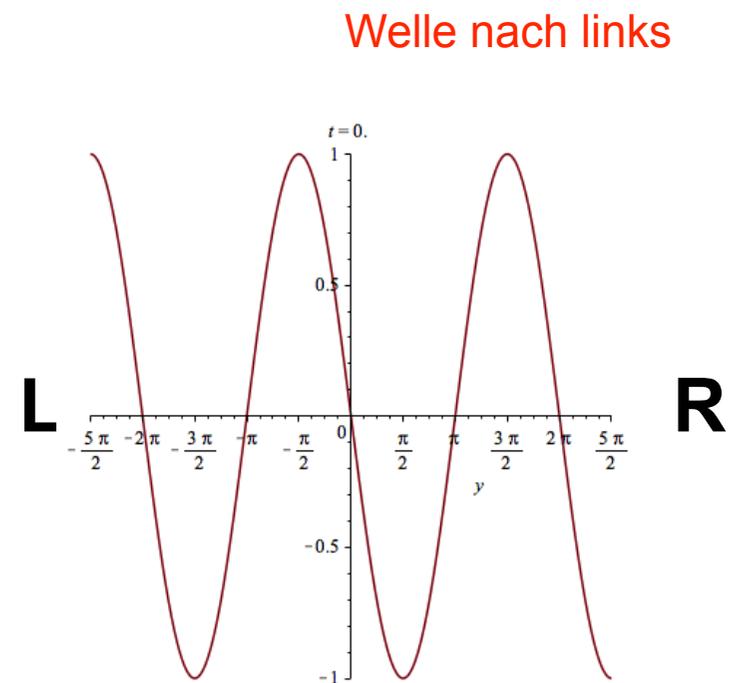
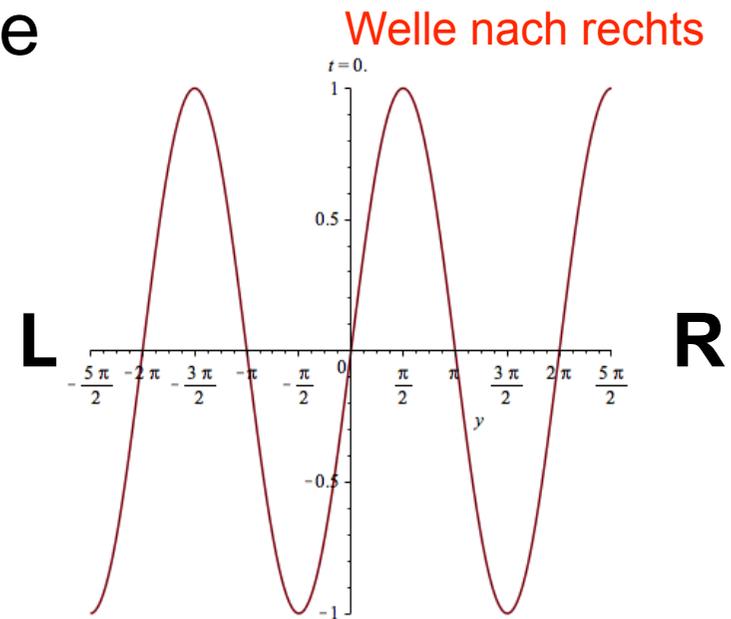
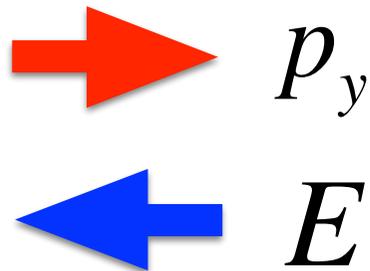
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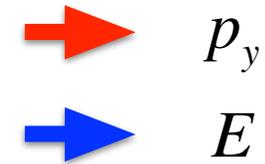
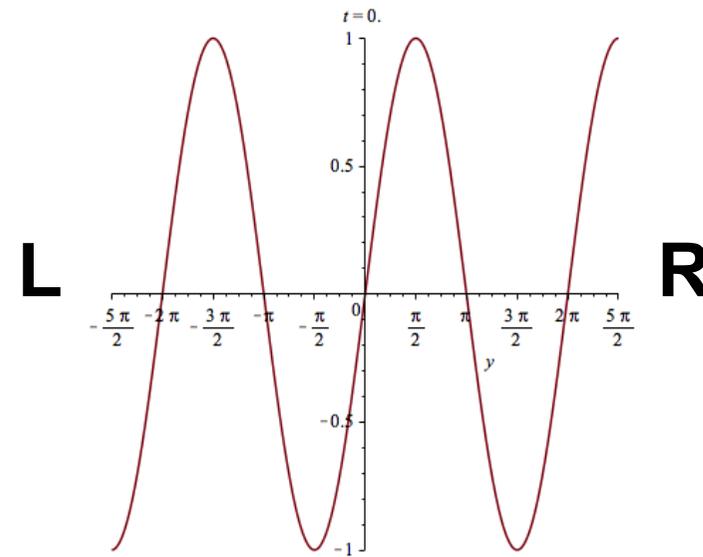
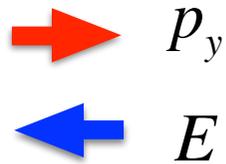
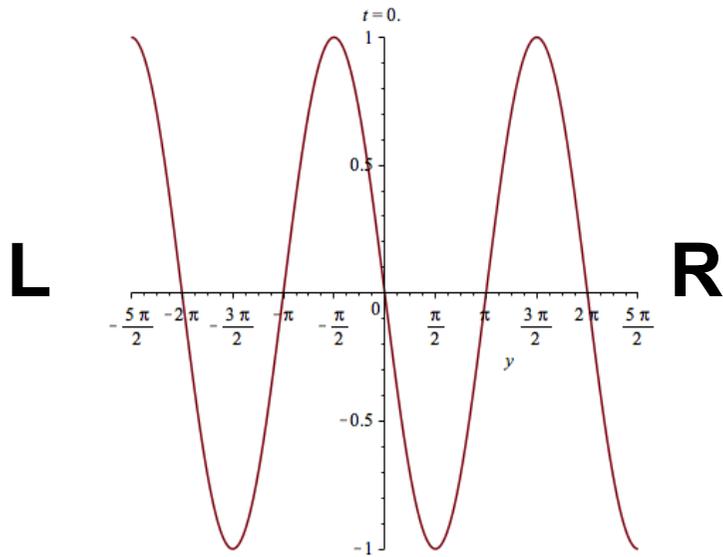
# B stehende elektromagnetische Welle



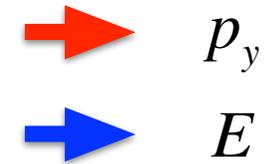
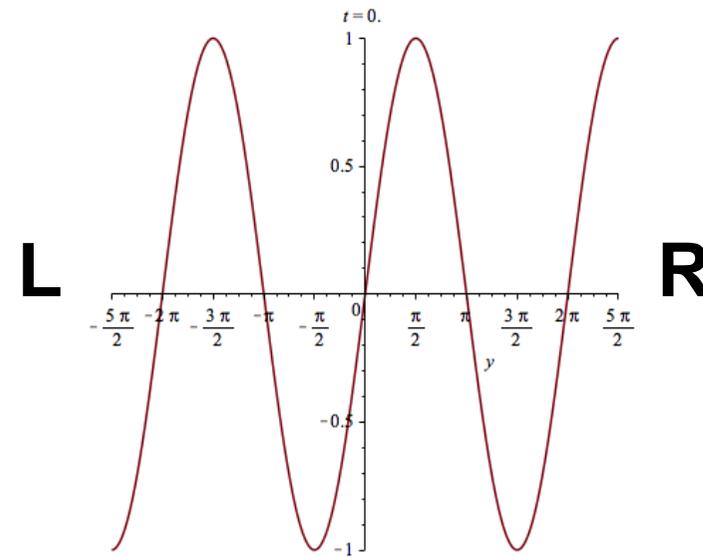
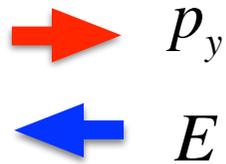
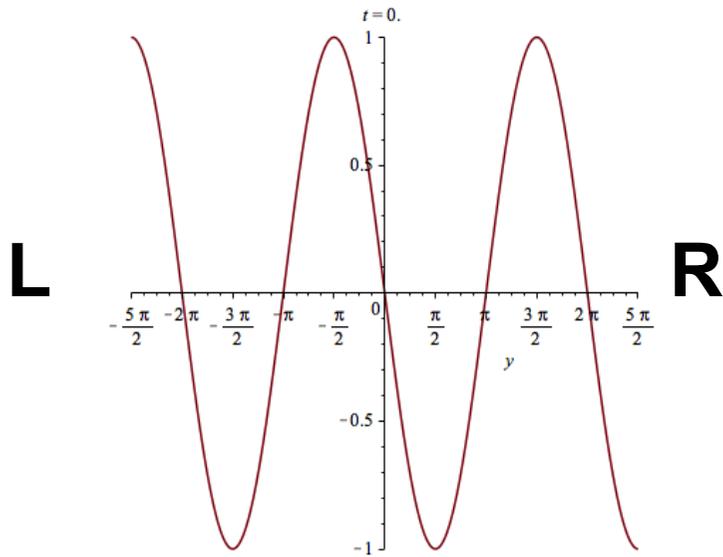
In beiden Wellen wird Impuls von L nach R transportiert



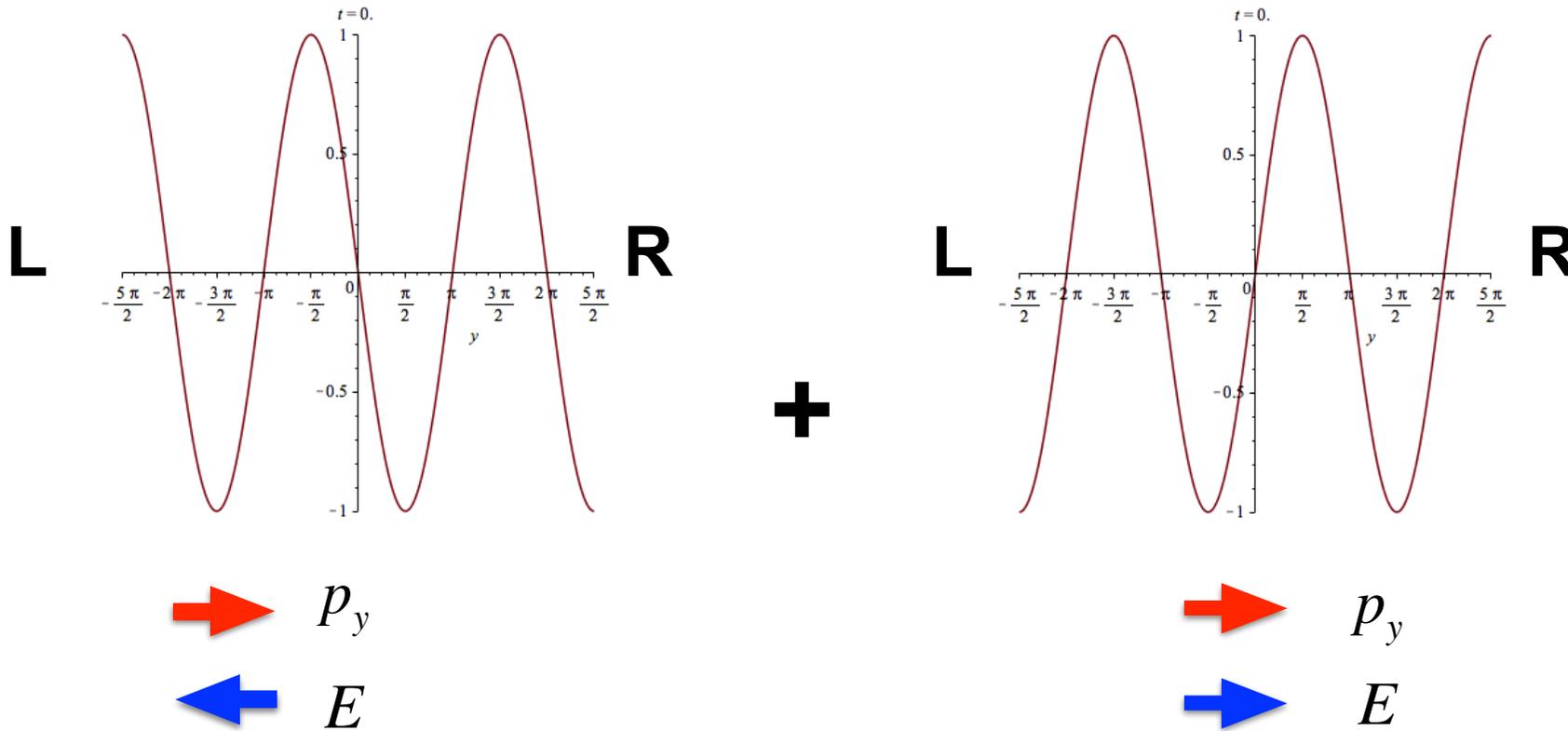
# B stehende elektromagnetische Welle



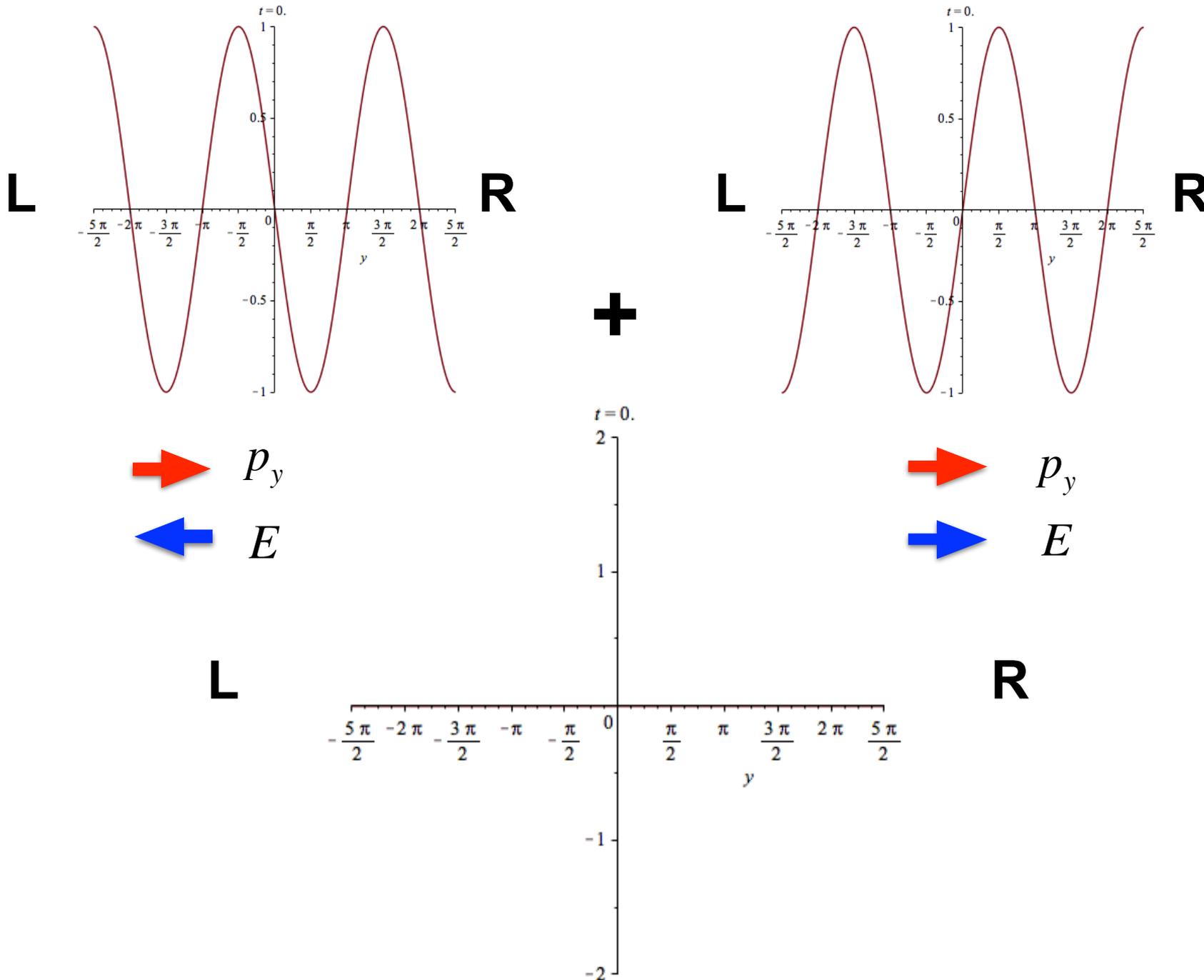
# B stehende elektromagnetische Welle



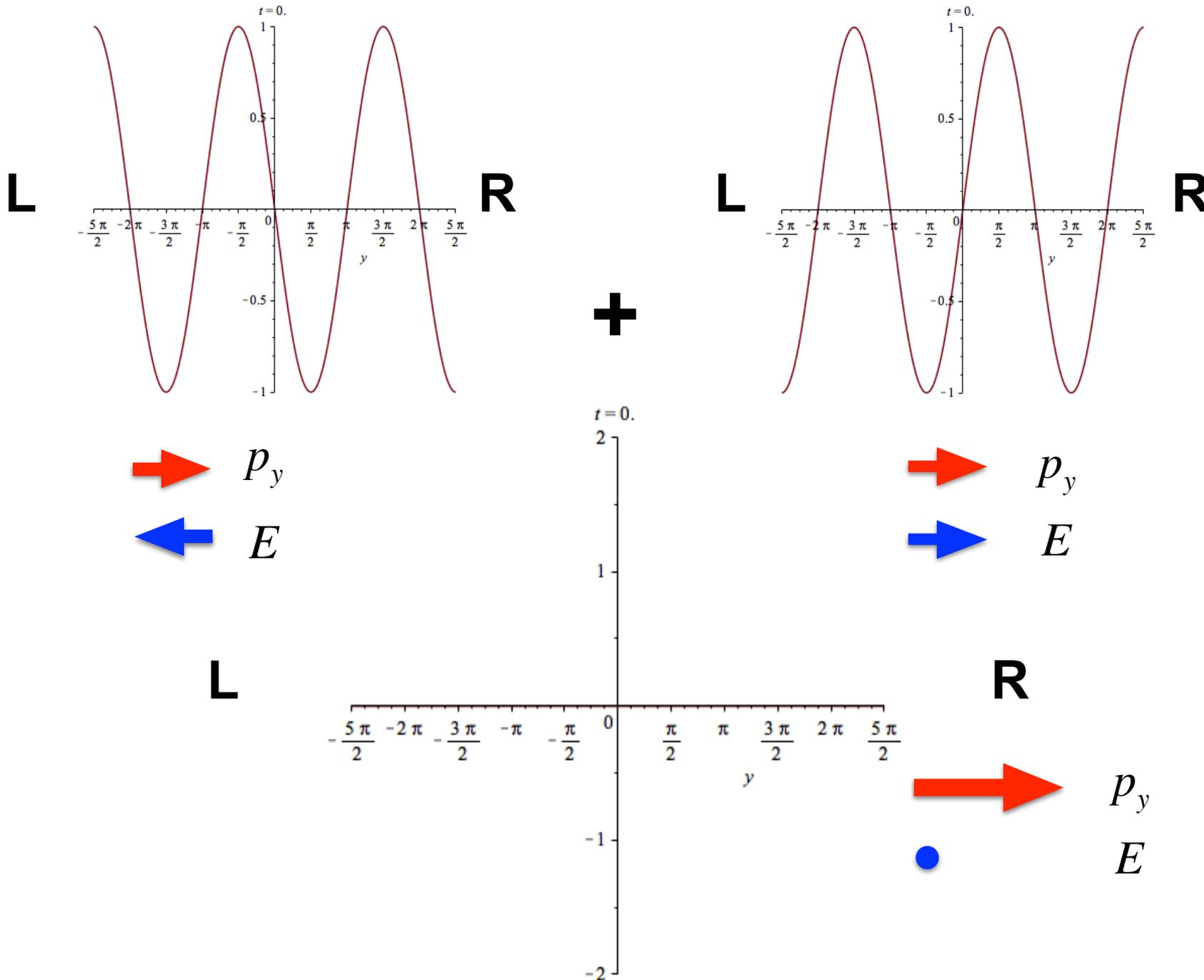
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle

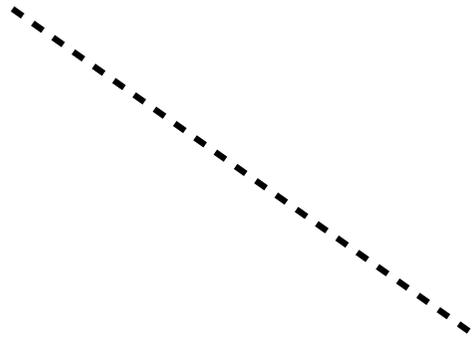


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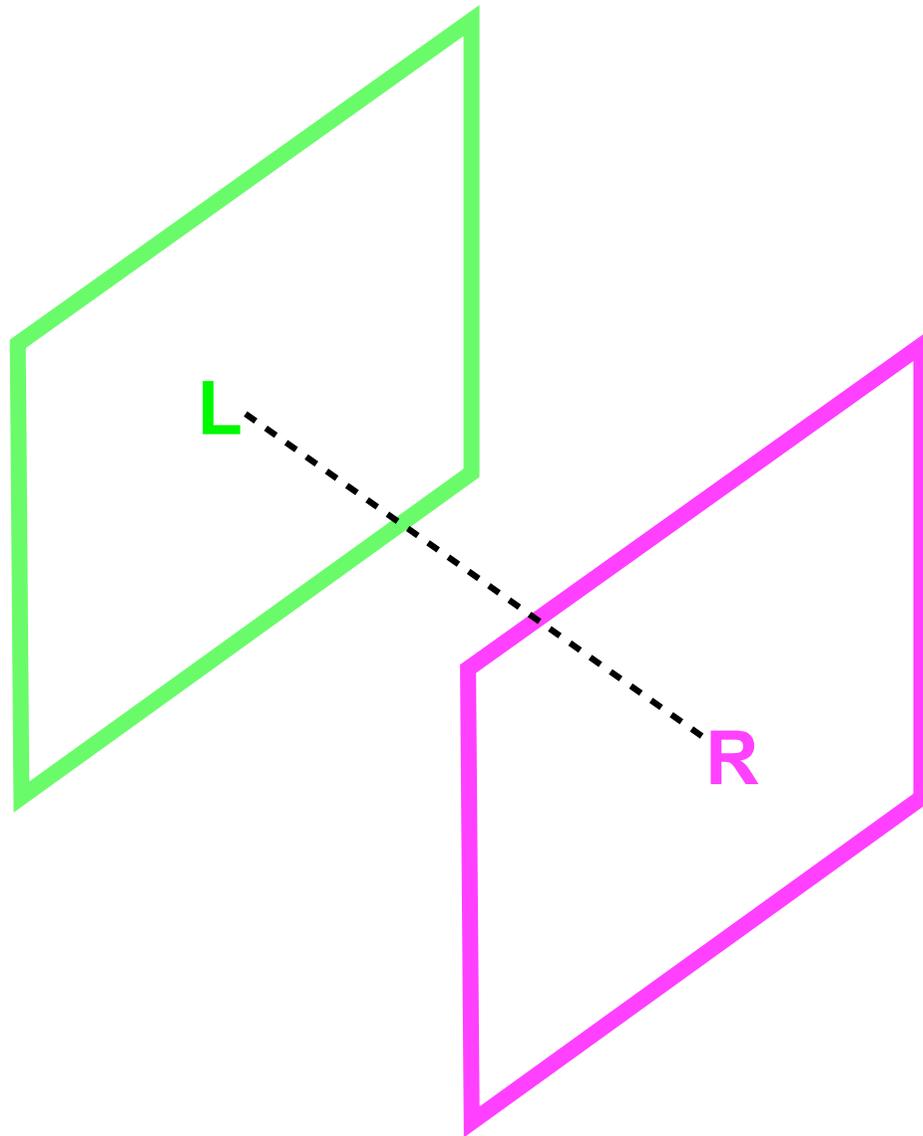


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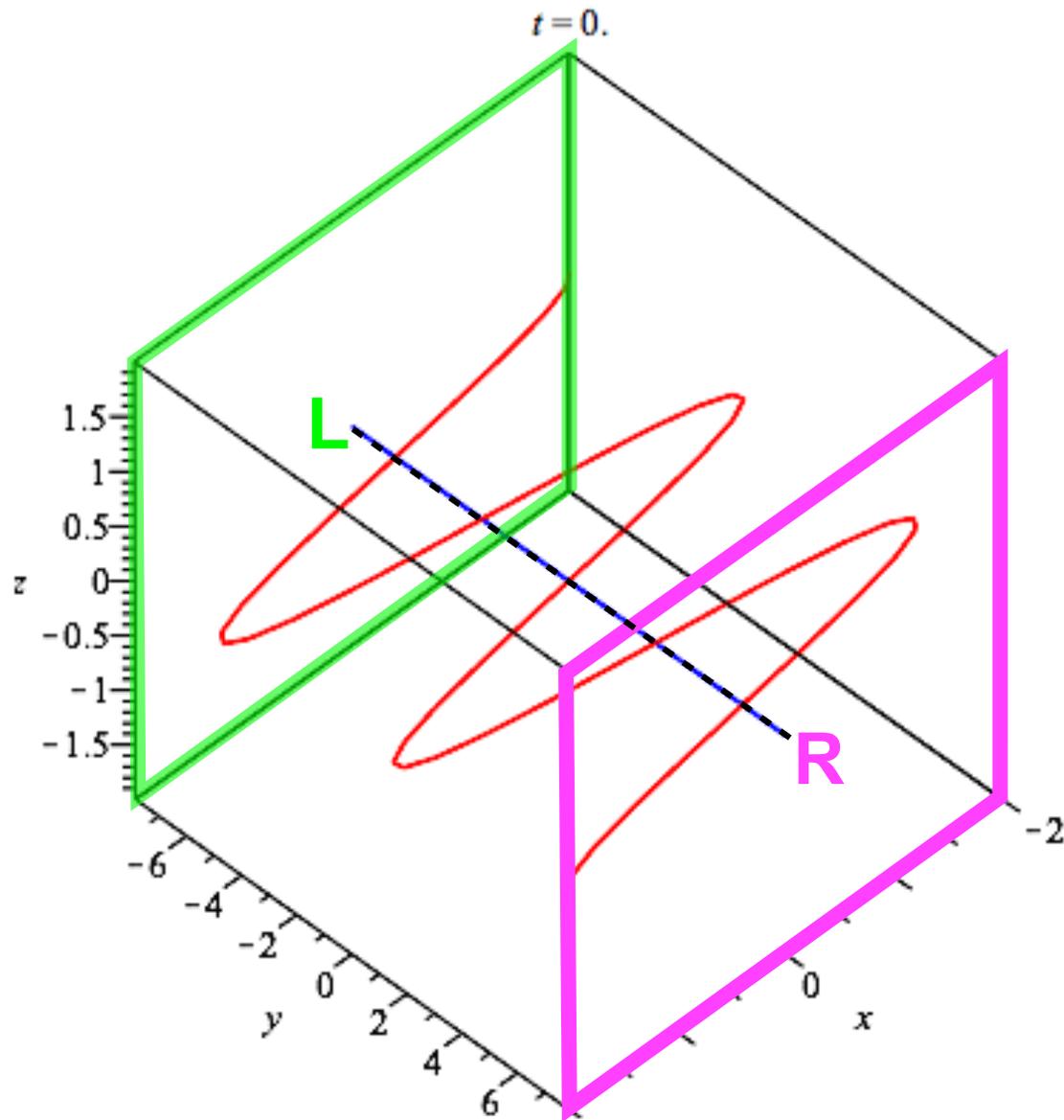
# B stehende elektromagnetische Welle



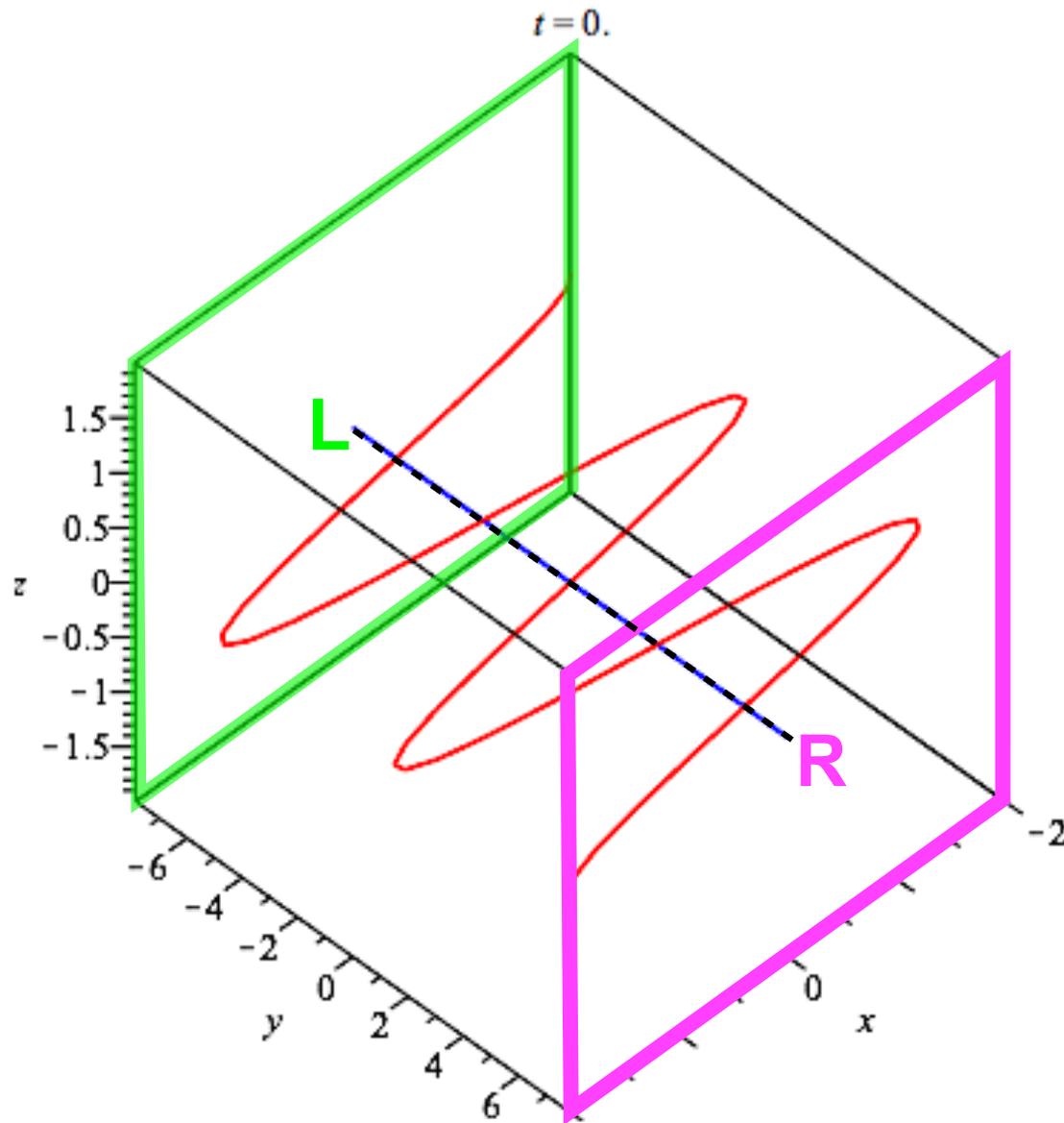
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle

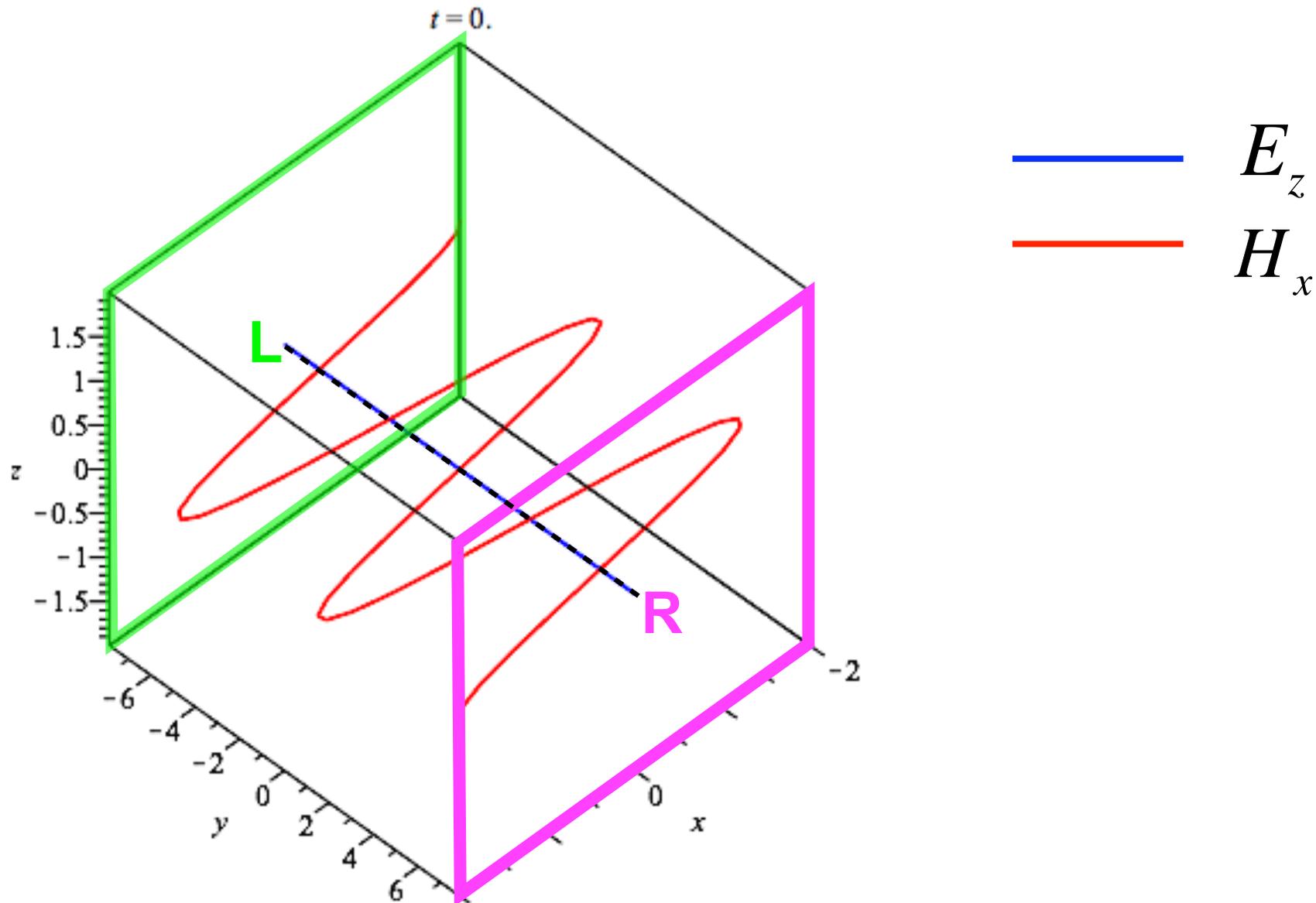


# B stehende elektromagnetische Welle

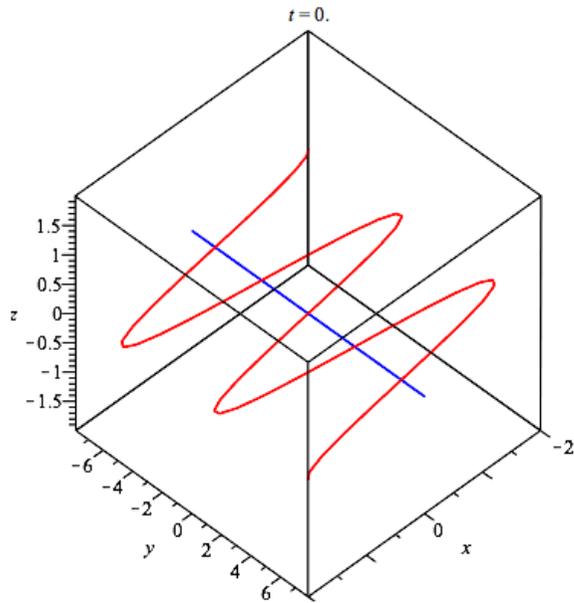


—  $E_z$

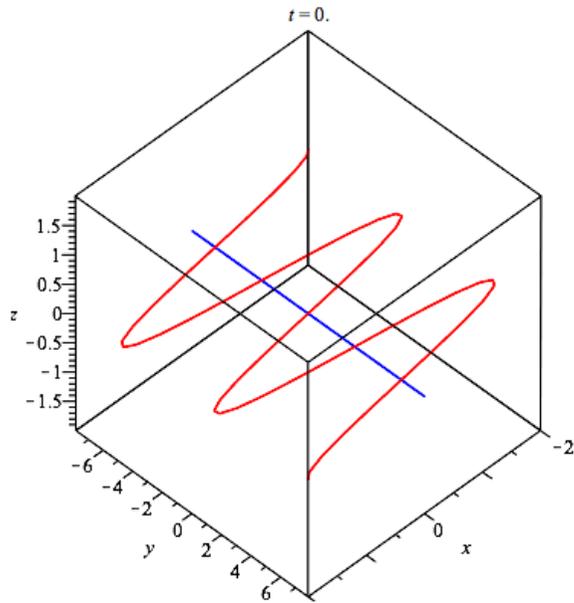
# B stehende elektromagnetische Welle



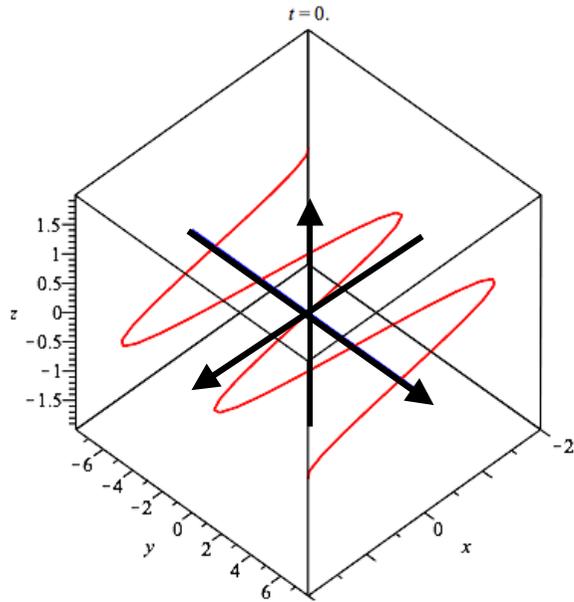
# B stehende elektromagnetische Welle



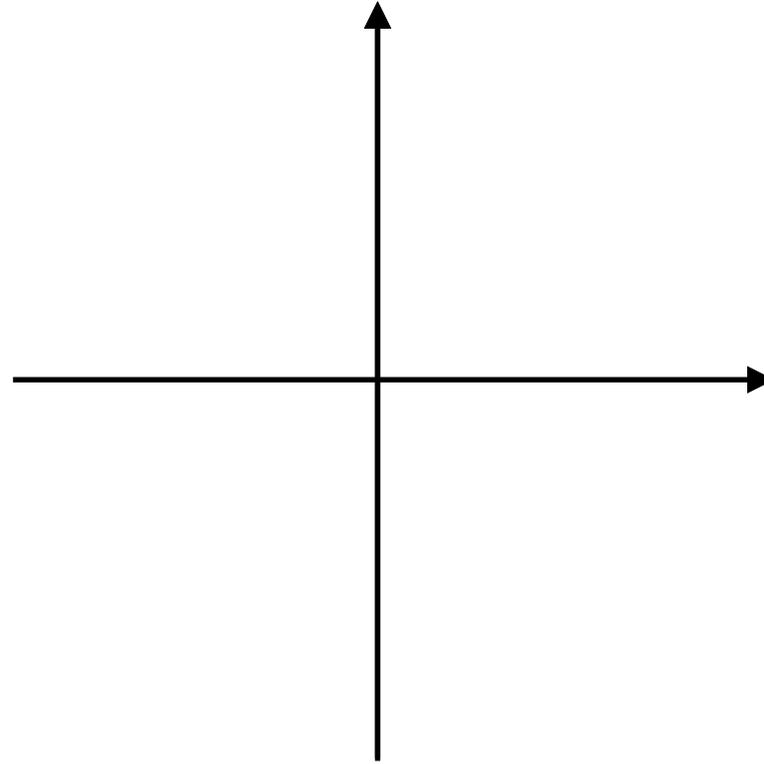
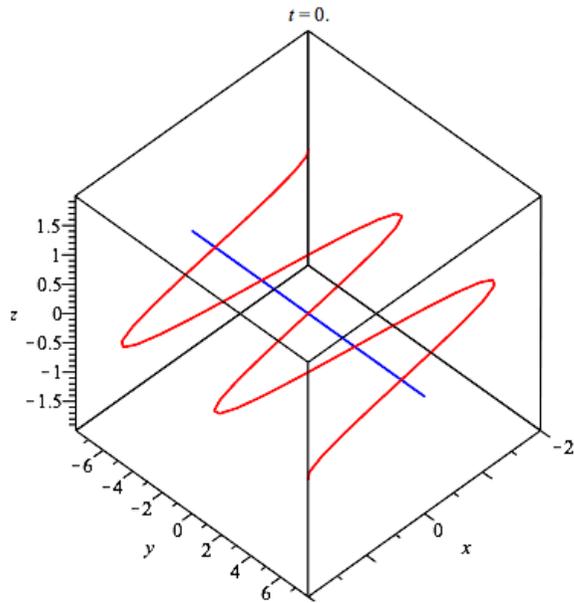
# B stehende elektromagnetische Welle



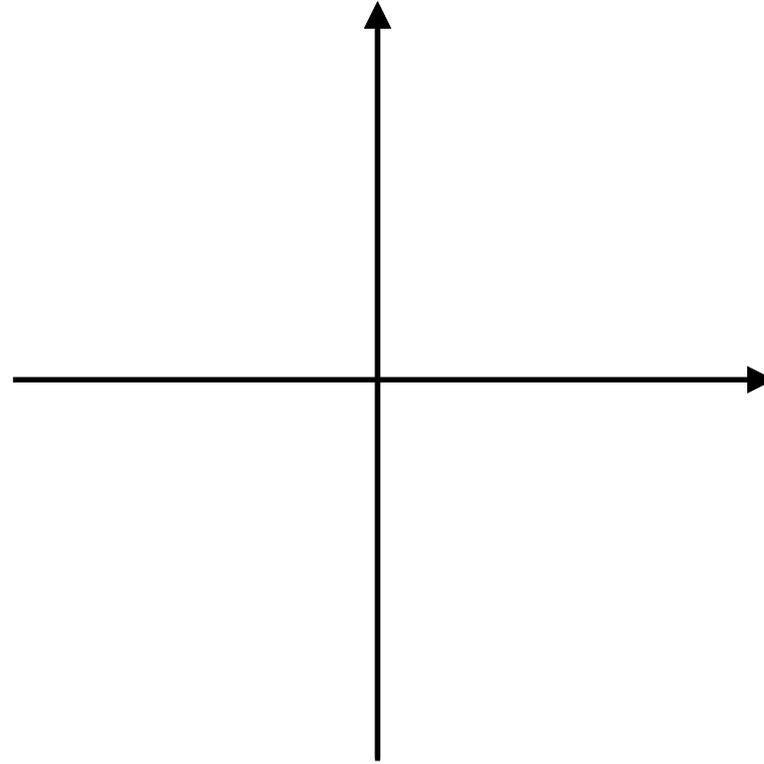
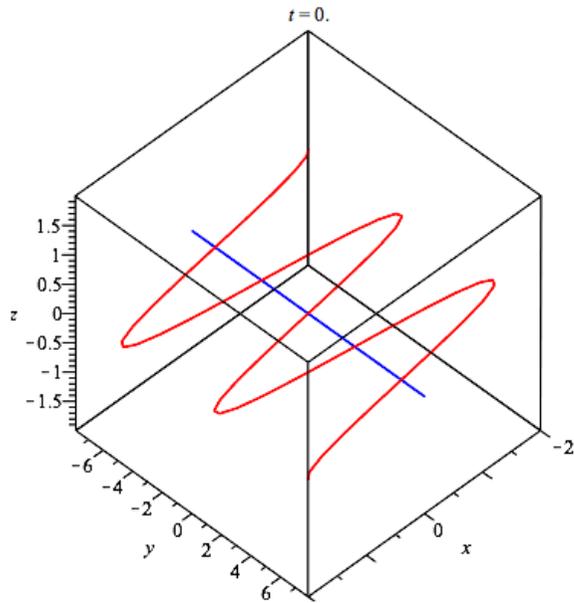
# B stehende elektromagnetische Welle



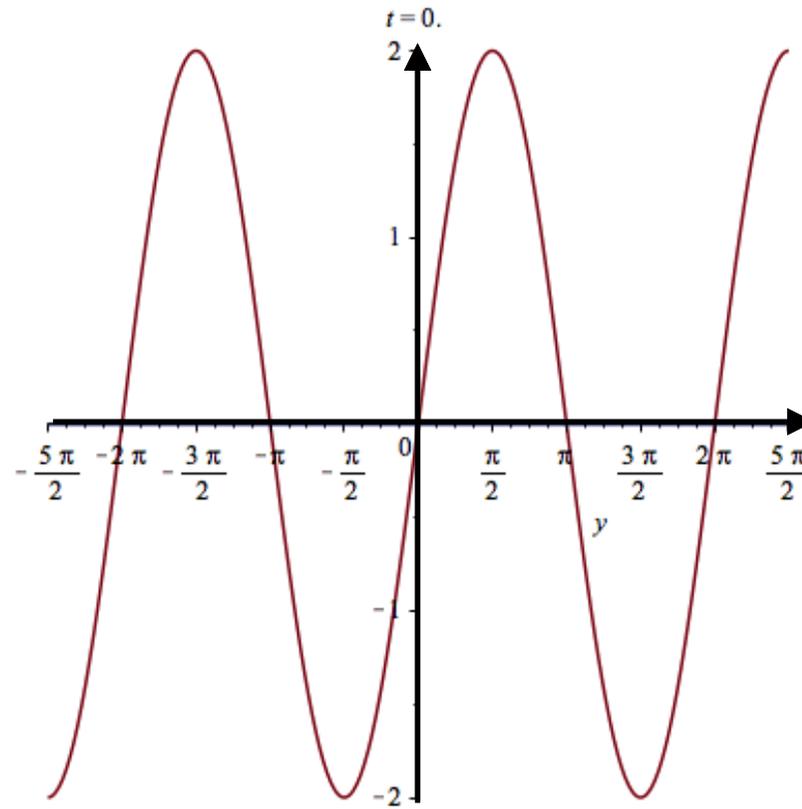
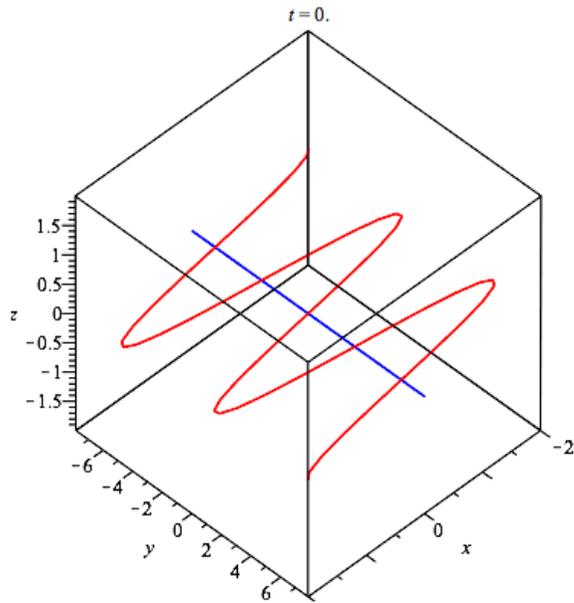
# B stehende elektromagnetische Welle



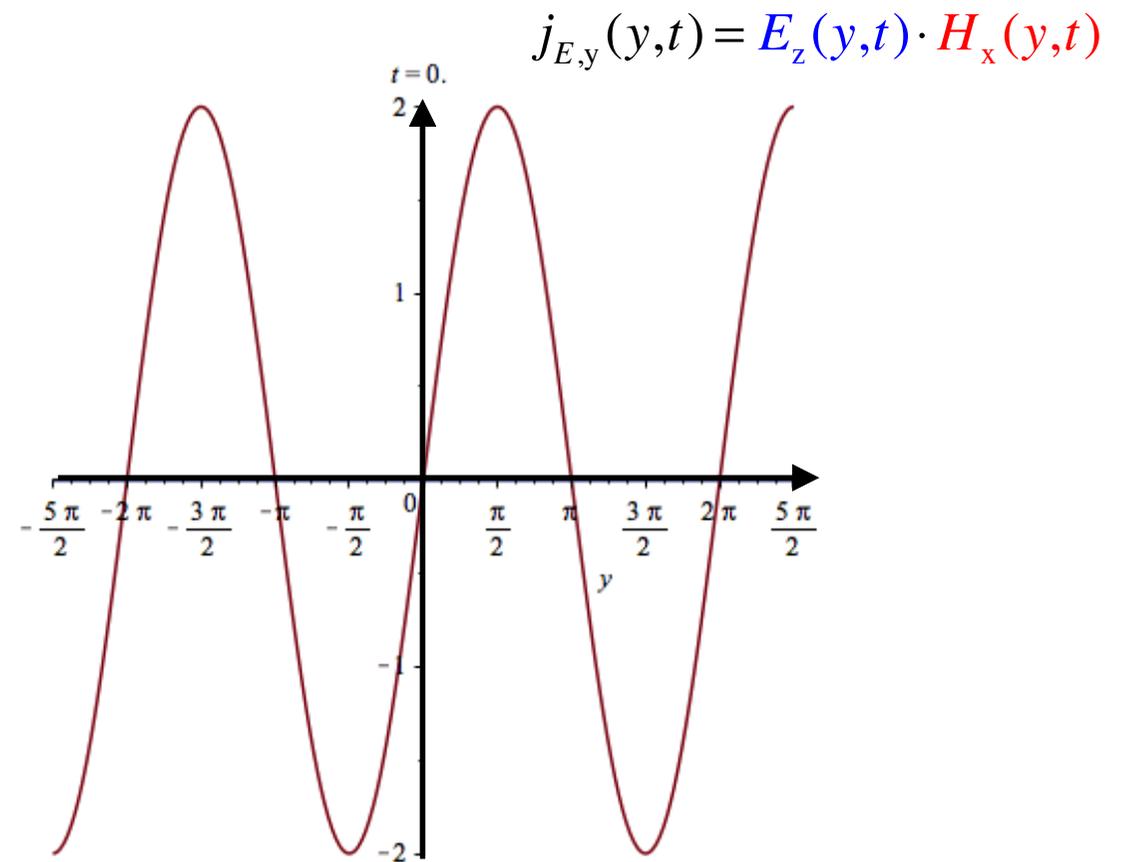
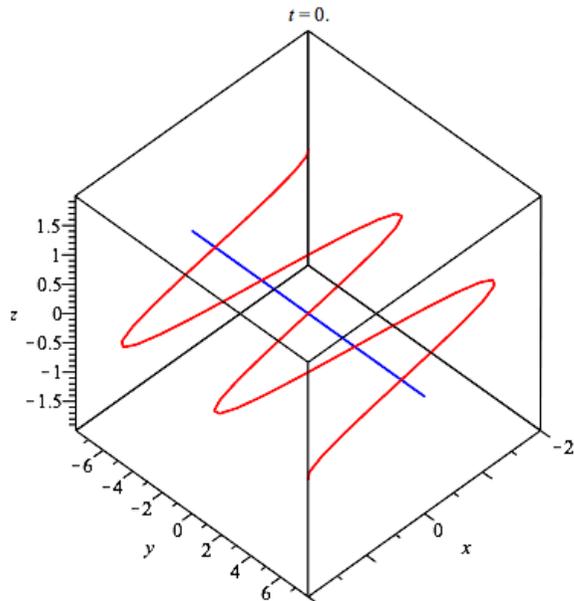
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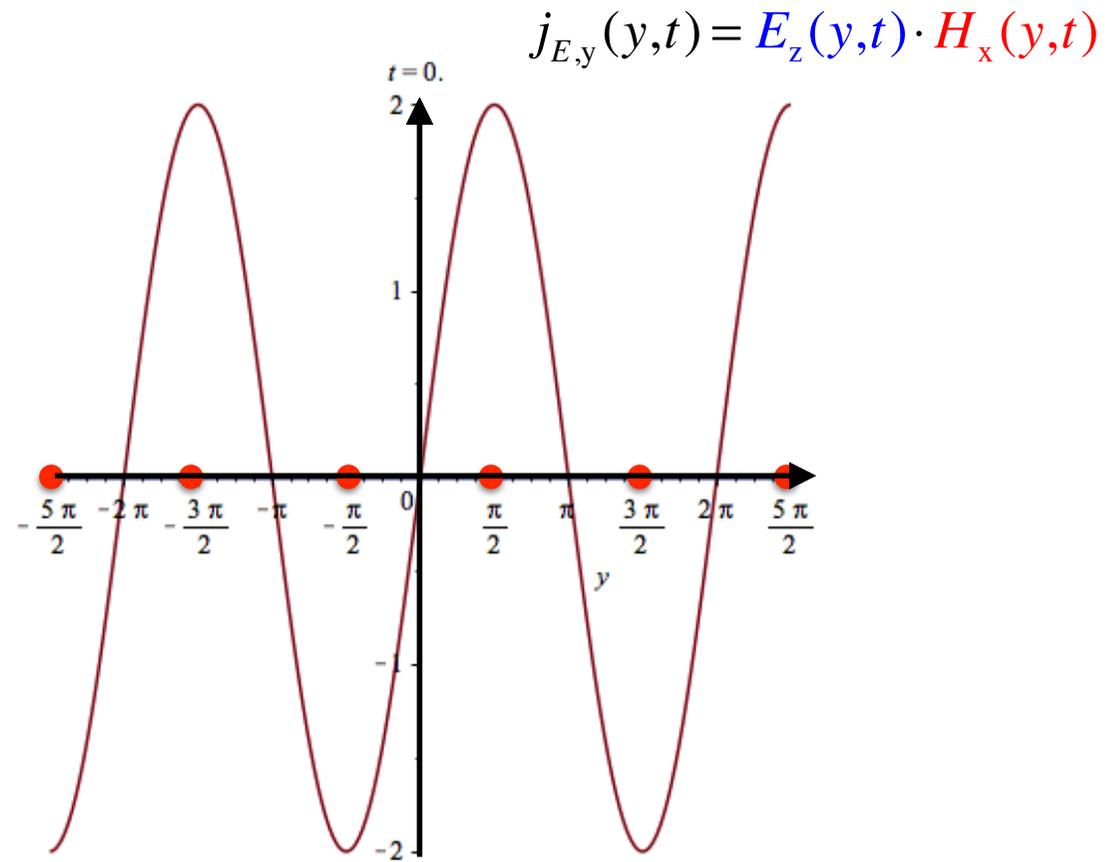
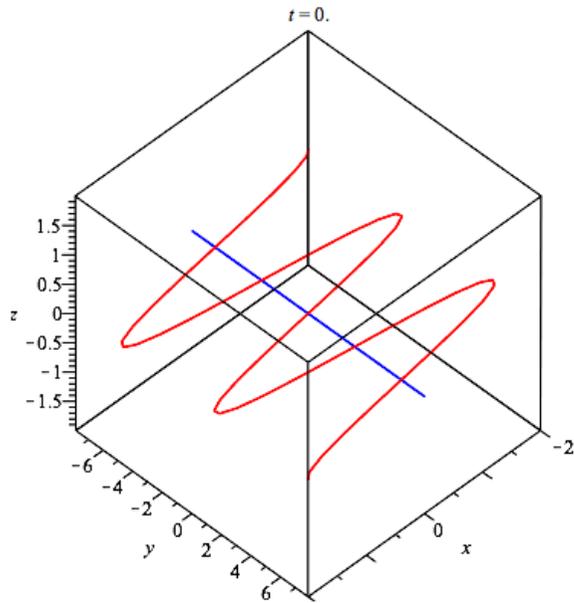
# B stehende elektromagnetische Welle



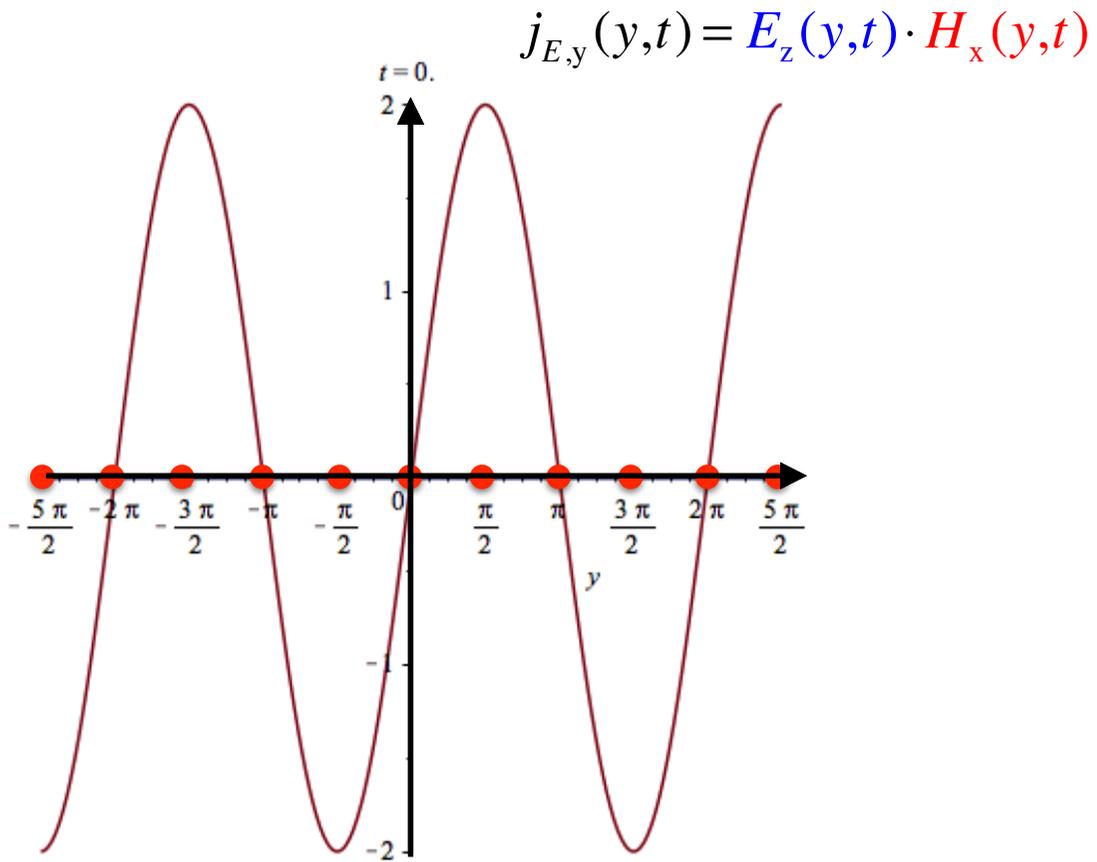
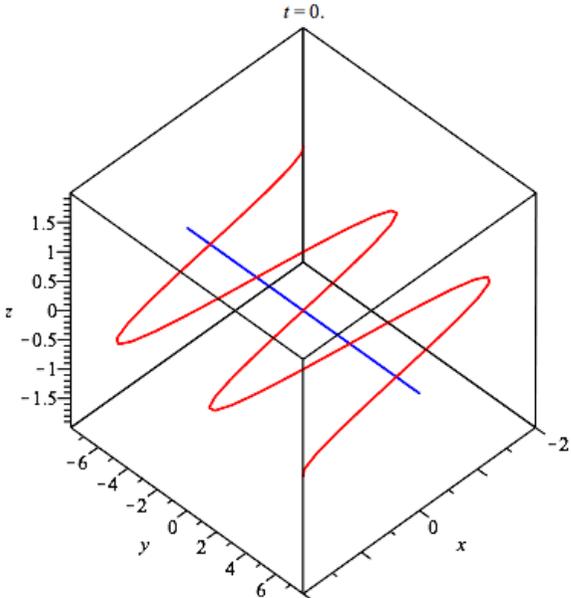
# B stehende elektromagnetische Welle



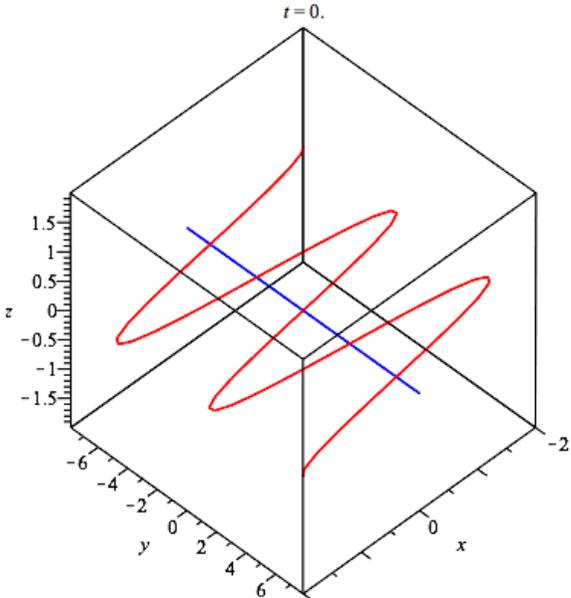
# B stehende elektromagnetische Welle



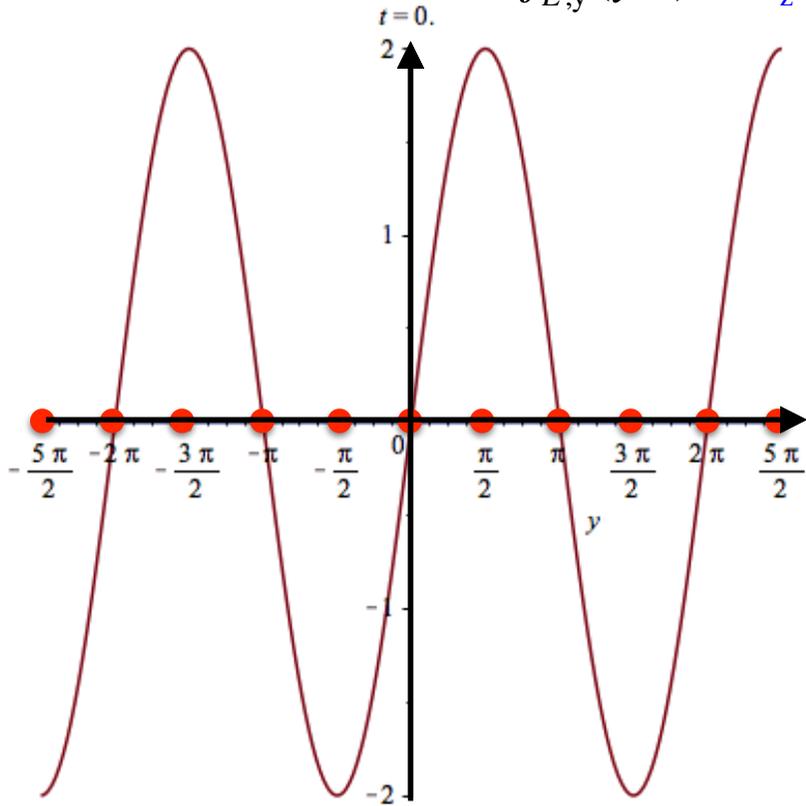
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle

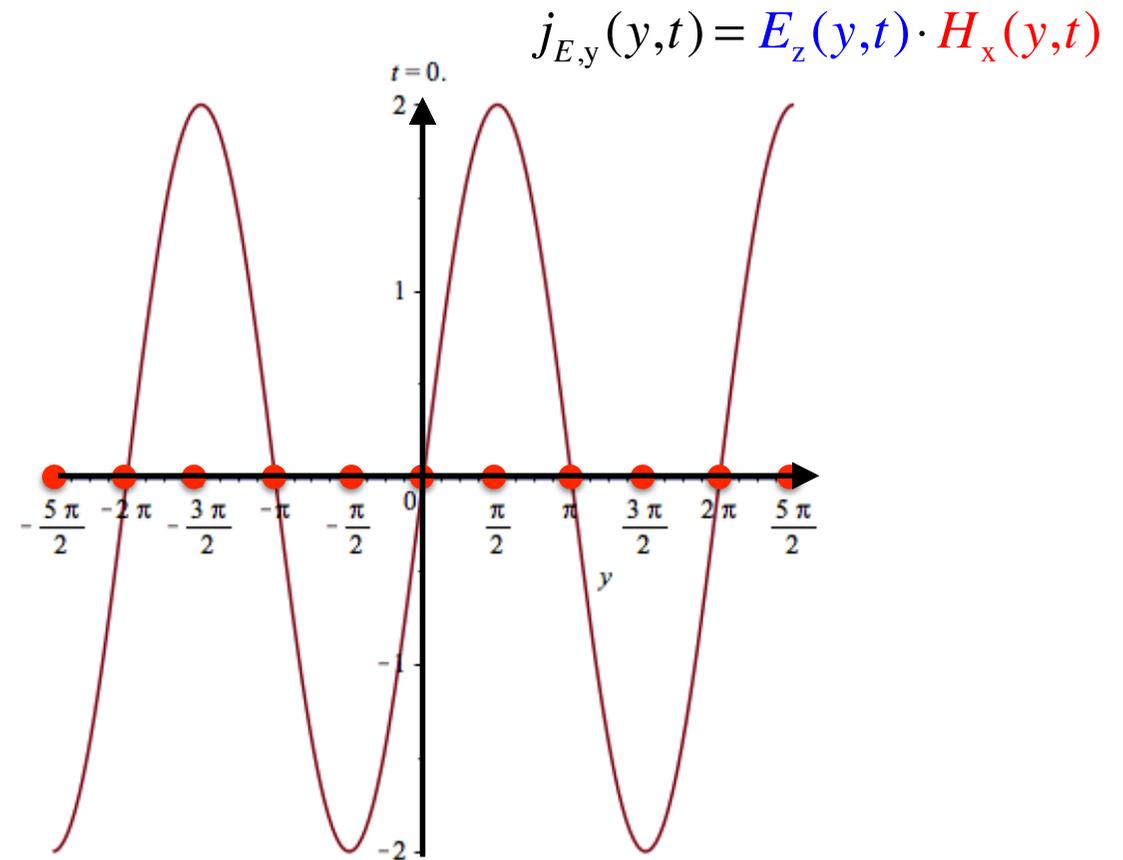
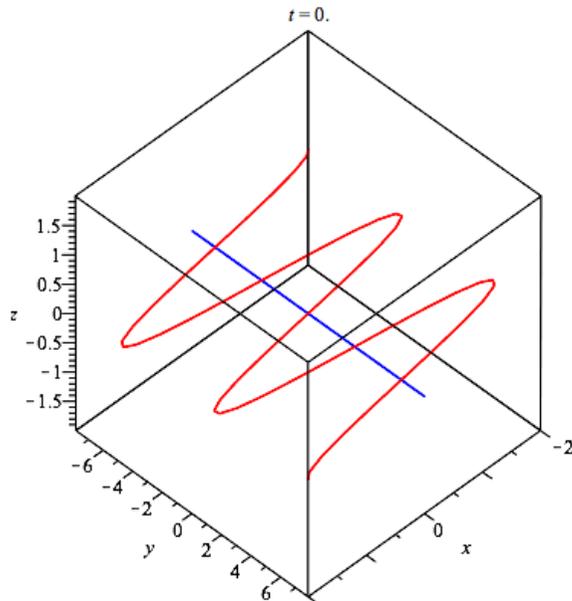


$$j_{E,y}(y,t) = E_z(y,t) \cdot H_x(y,t)$$



● Energiestromdichte  $j_{E,y} = 0$

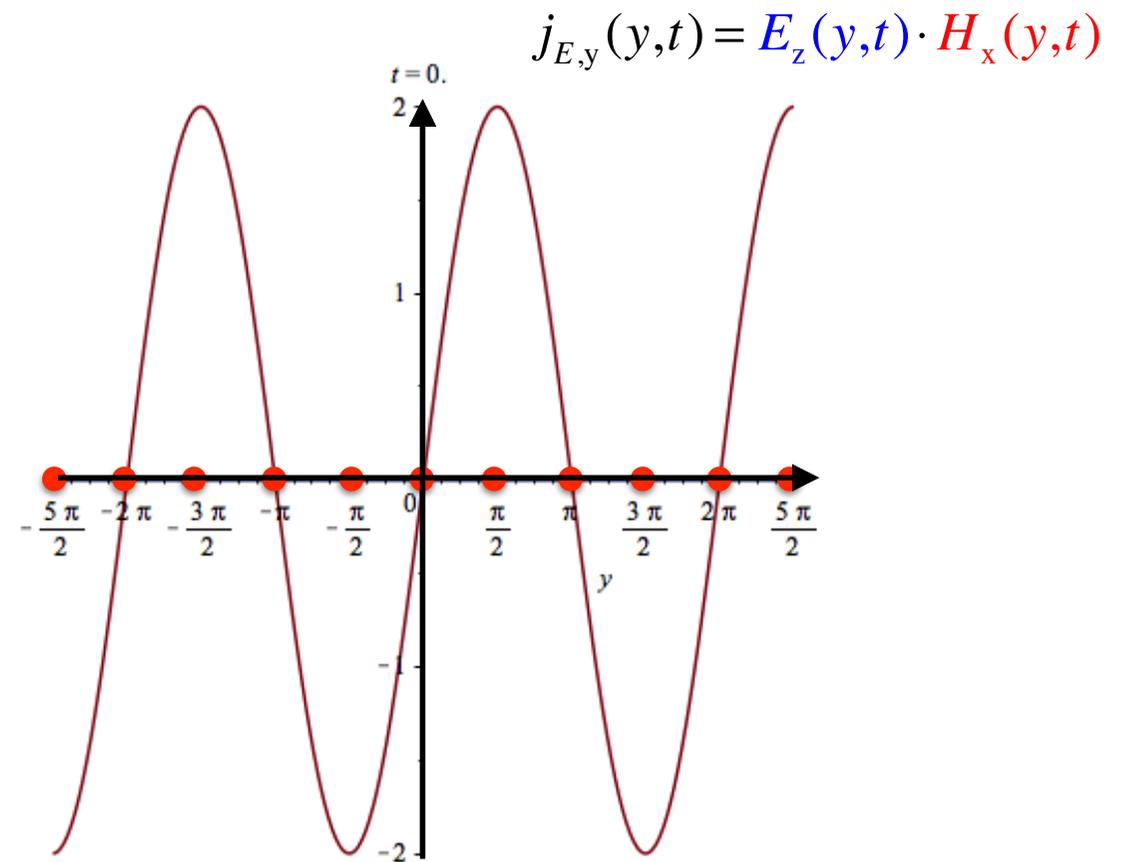
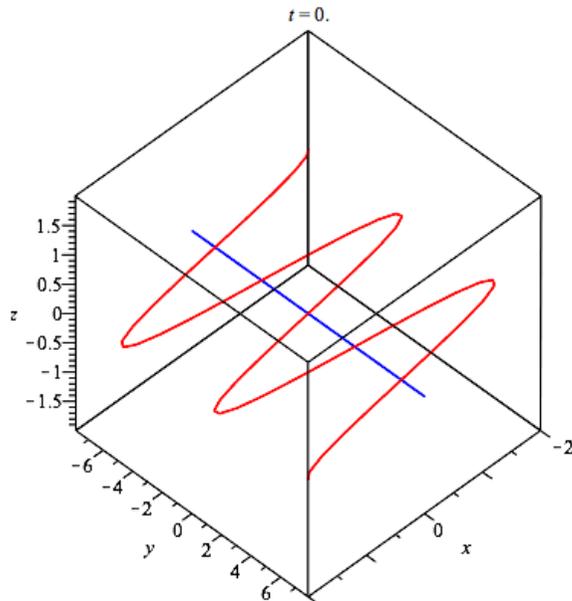
# B stehende elektromagnetische Welle



● Energiestromdichte  $j_{E,y} = 0$

dazwischen

# B stehende elektromagnetische Welle

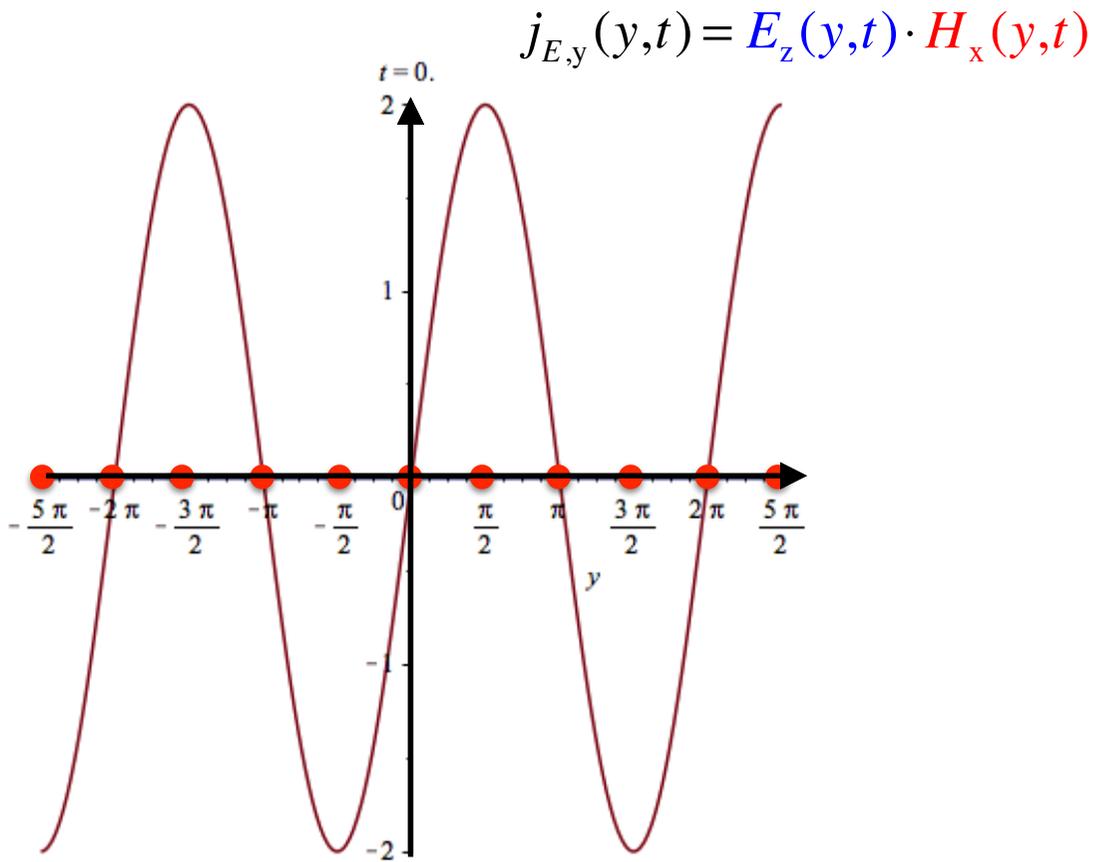
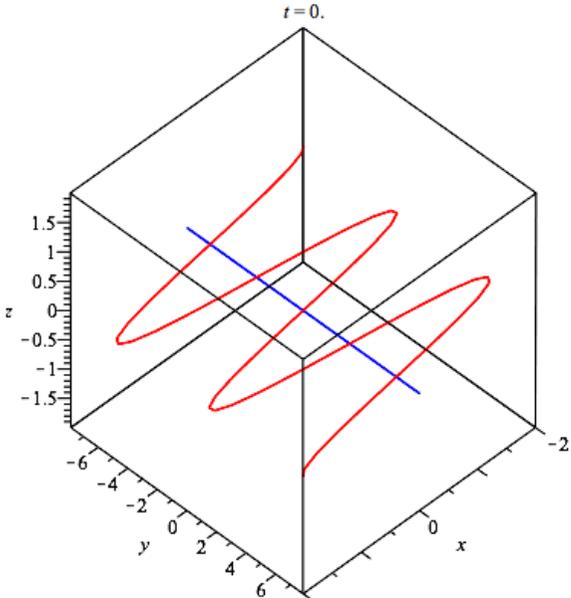


● Energiestromdichte  $j_{E,y} = 0$

dazwischen

nach rechts wenn  $E_z \cdot H_x > 0$

# B stehende elektromagnetische Welle



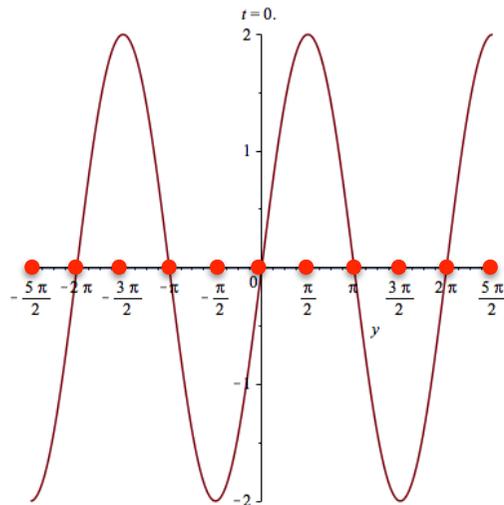
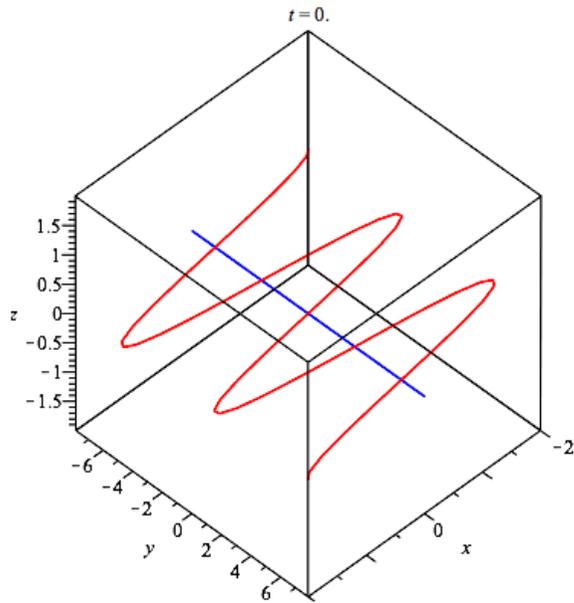
● Energiestromdichte  $j_{E,y} = 0$

dazwischen

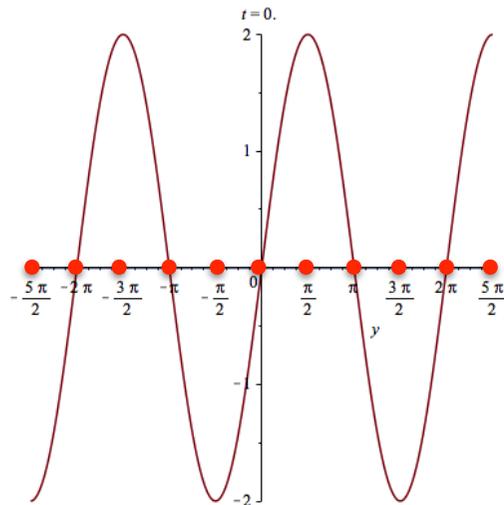
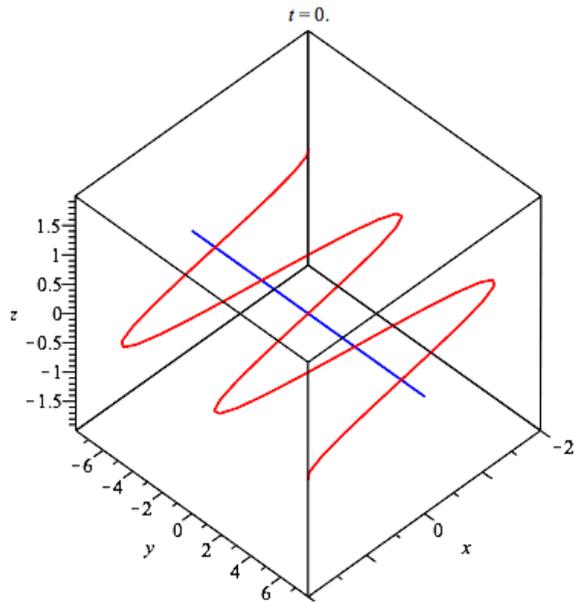
nach rechts wenn  $E_z \cdot H_x > 0$

nach links wenn  $E_z \cdot H_x < 0$

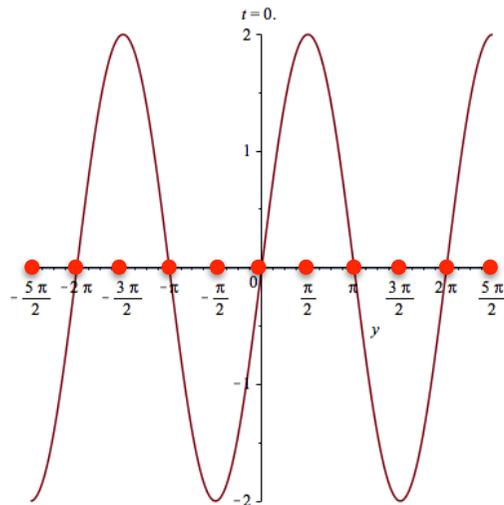
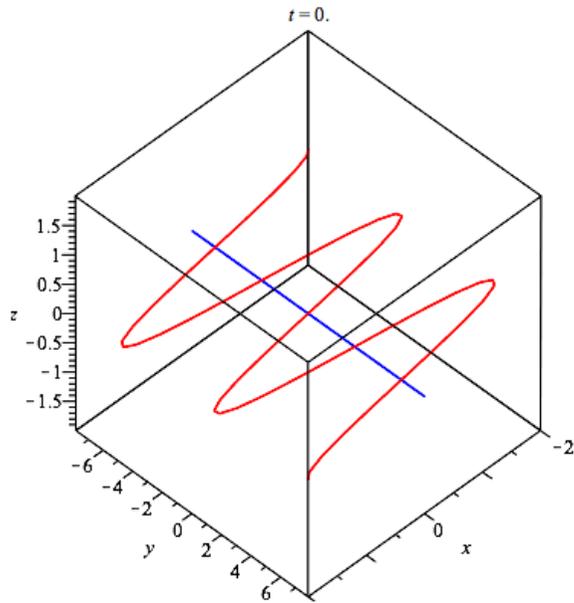
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle

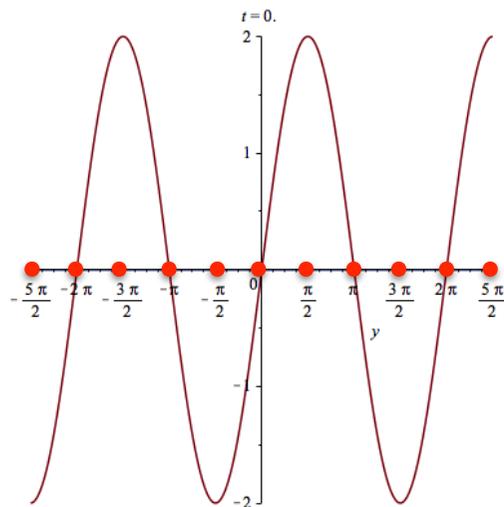
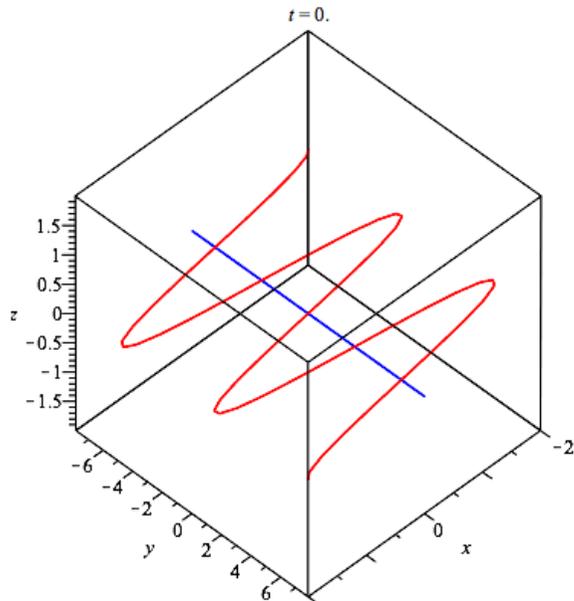


# B stehende elektromagnetische Welle

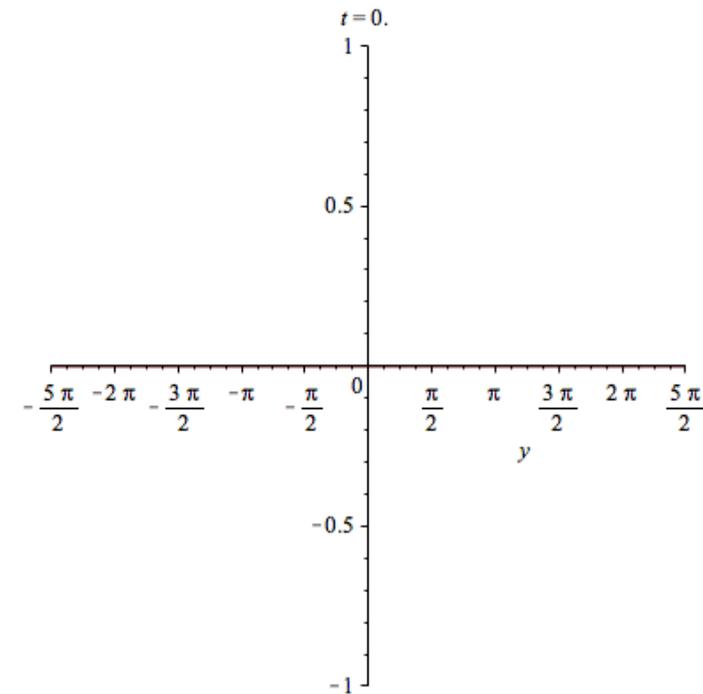


$$j_{E,y}(y,t)$$

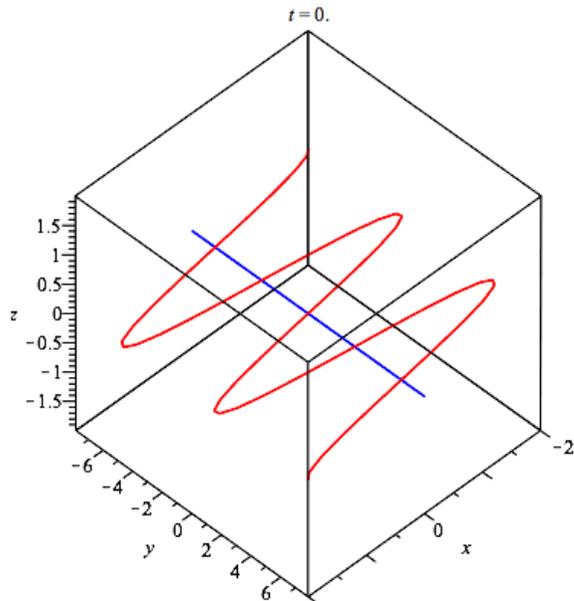
# B stehende elektromagnetische Welle



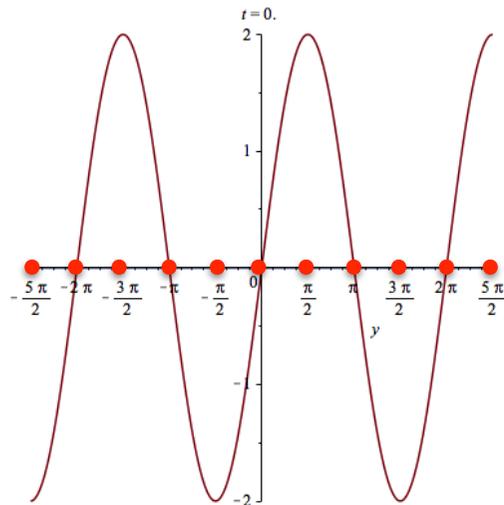
$$j_{E,y}(y,t)$$



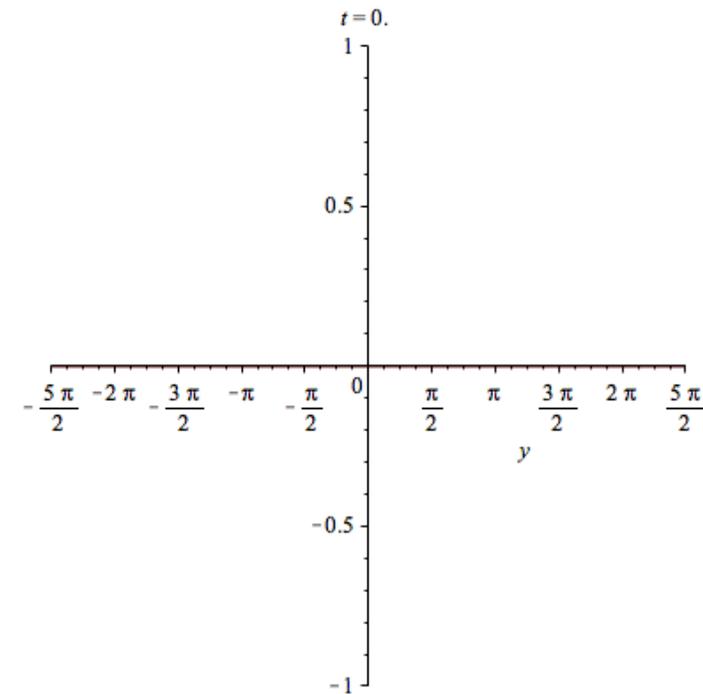
# B stehende elektromagnetische Welle



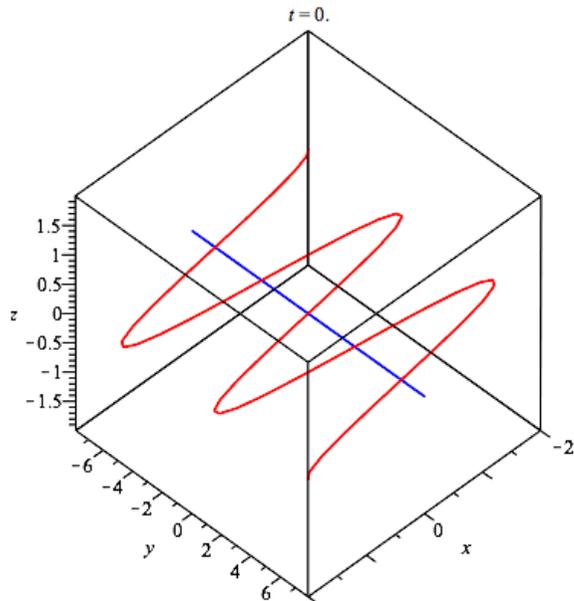
$$\rho_E(y,t)$$



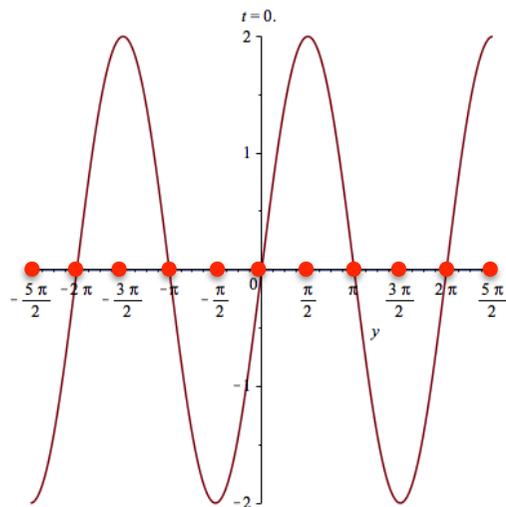
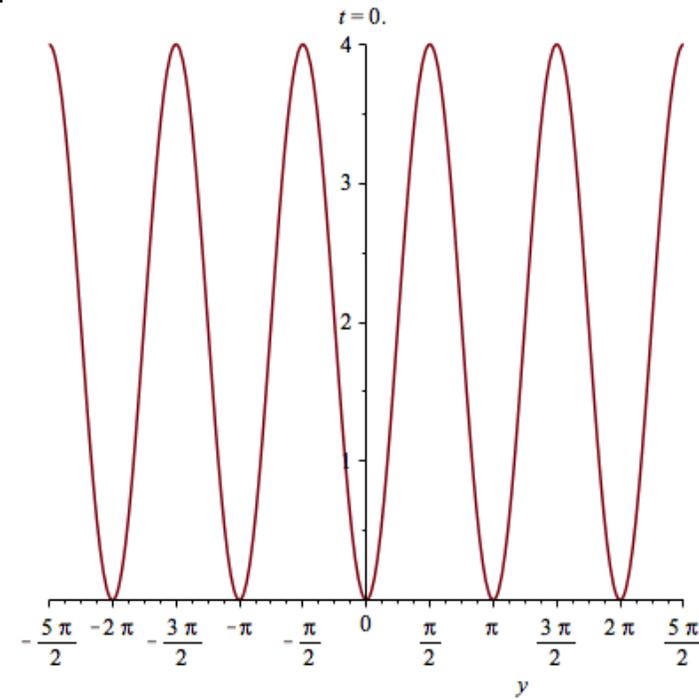
$$j_{E,y}(y,t)$$



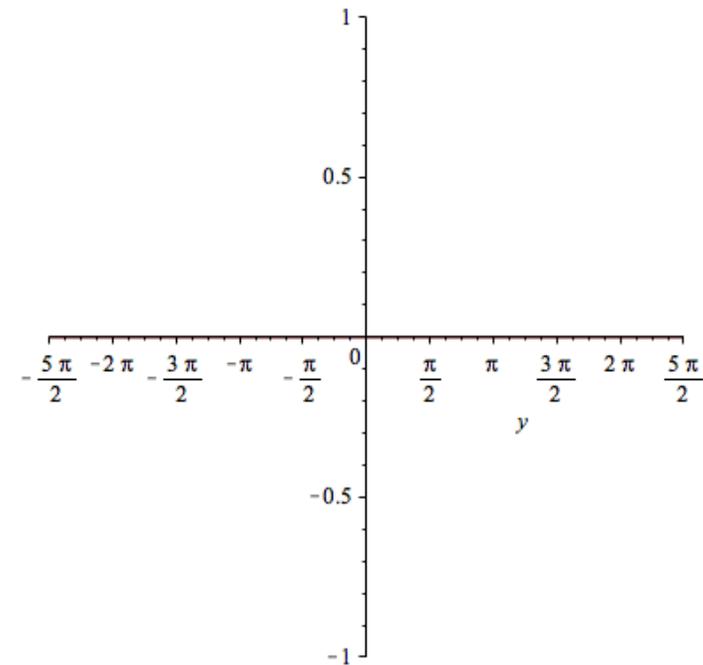
# B stehende elektromagnetische Welle



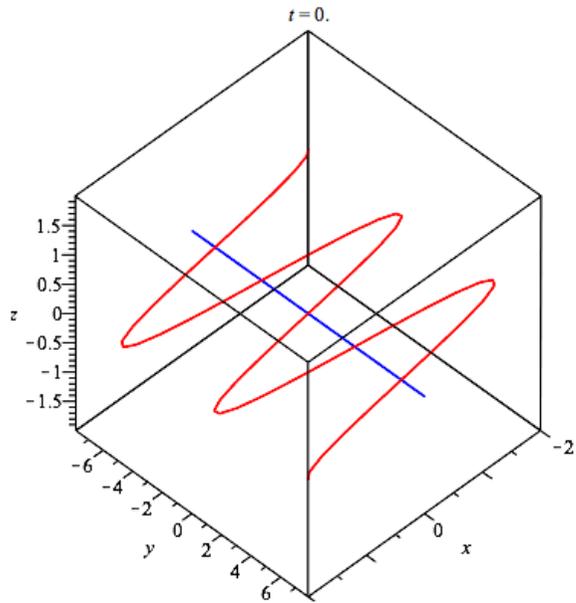
$$\rho_E(y,t)$$



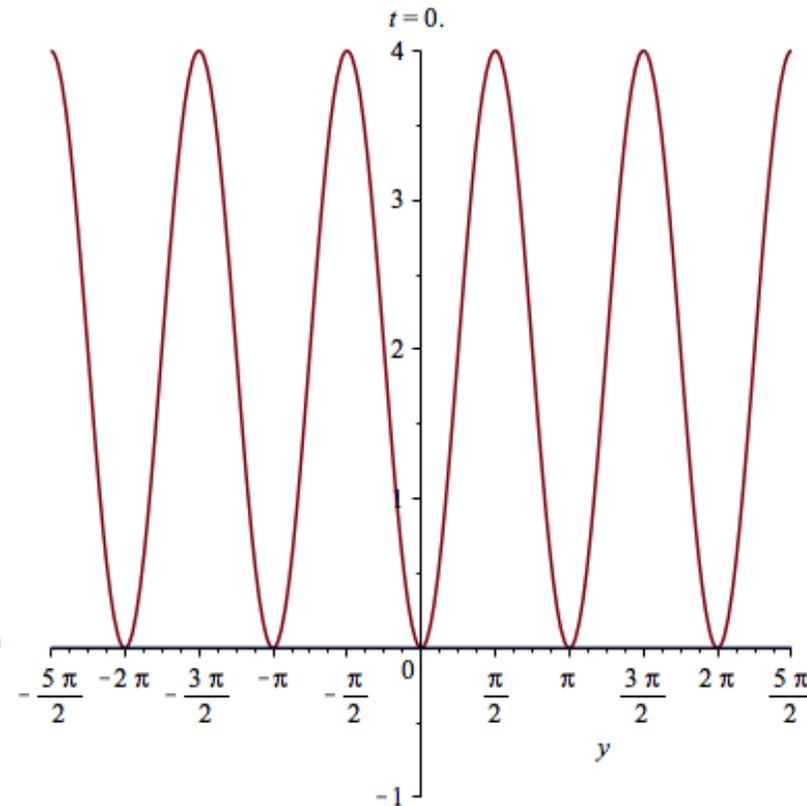
$$j_{E,y}(y,t)$$



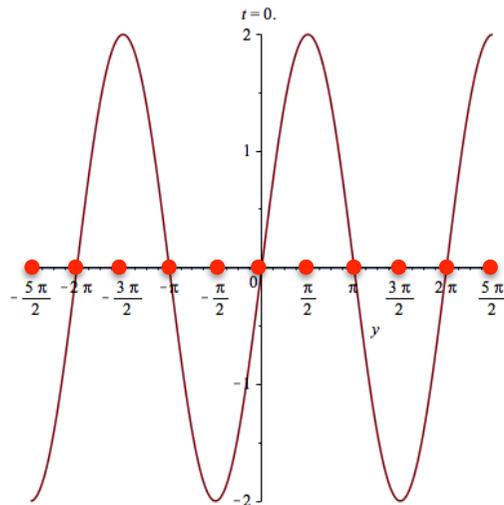
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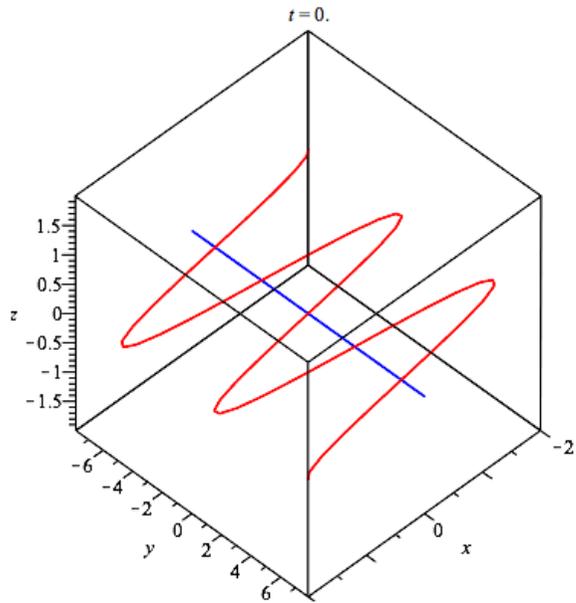
$$\rho_E(y,t)$$



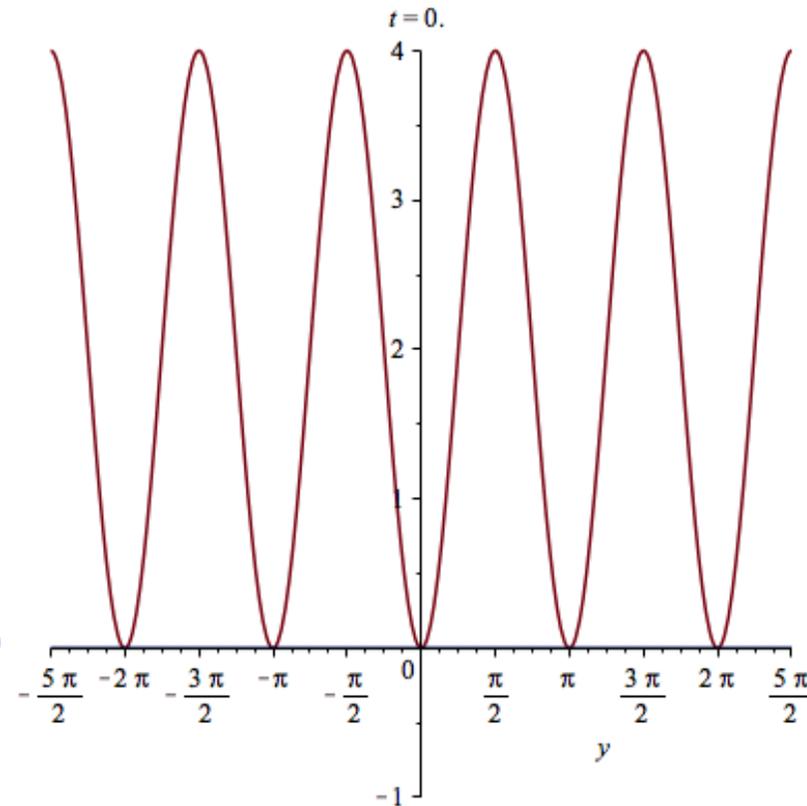
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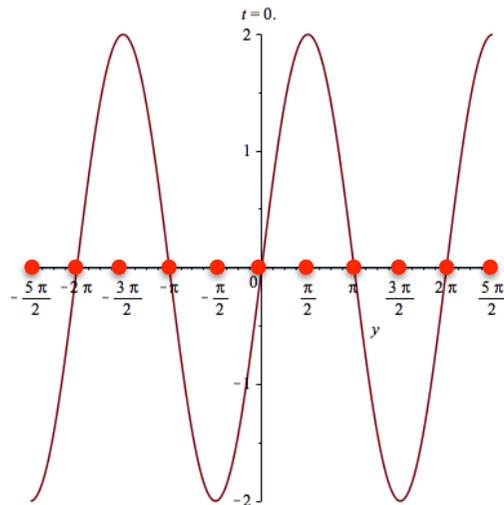
# B stehende elektromagnetische Welle



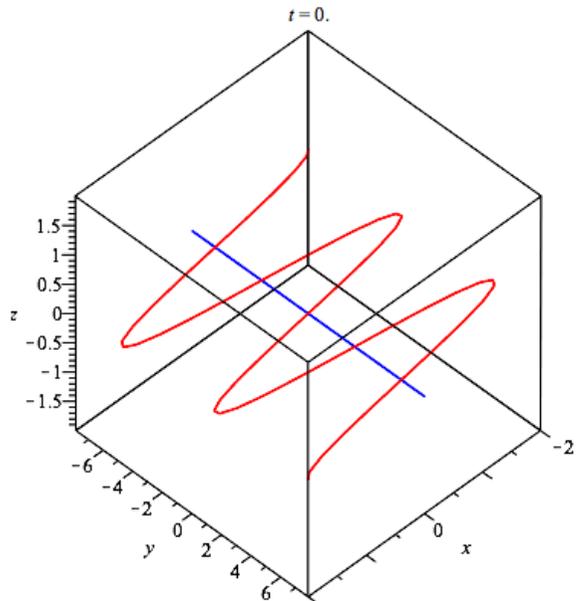
$$\rho_E(y,t)$$



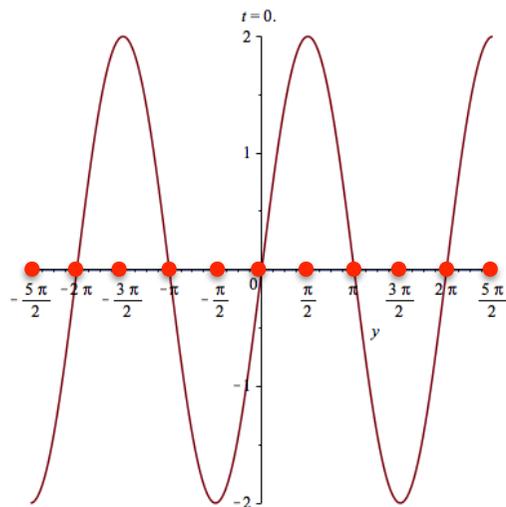
$$j_{E,y}(y,t)$$



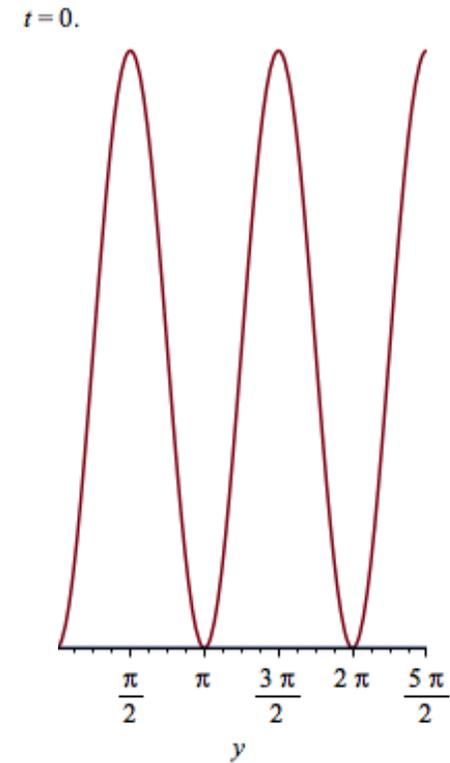
# B stehende elektromagnetische Welle



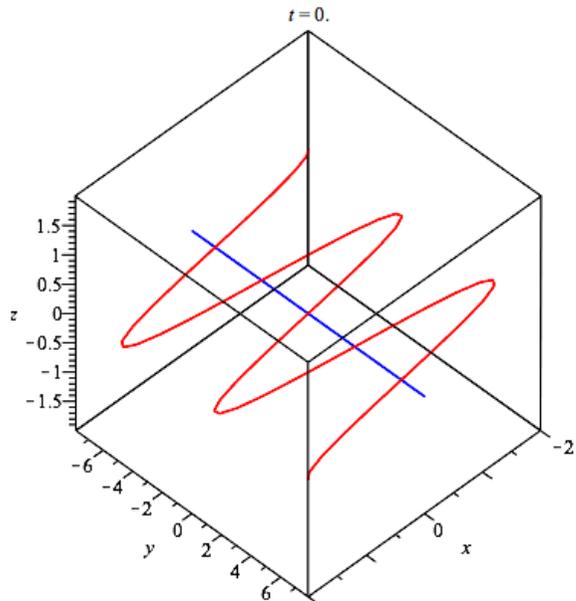
$$\rho_E(y,t)$$



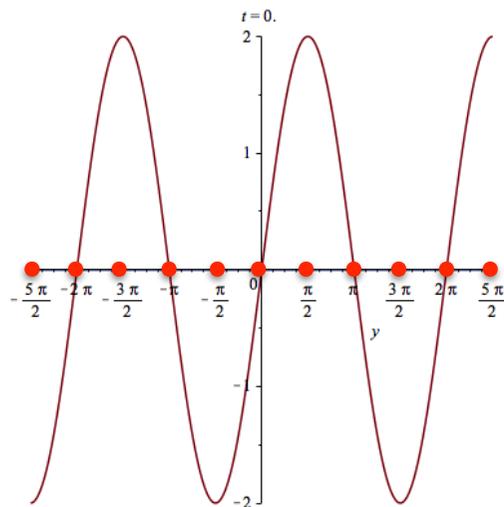
$$j_{E,y}(y,t)$$



# B stehende elektromagnetische Welle

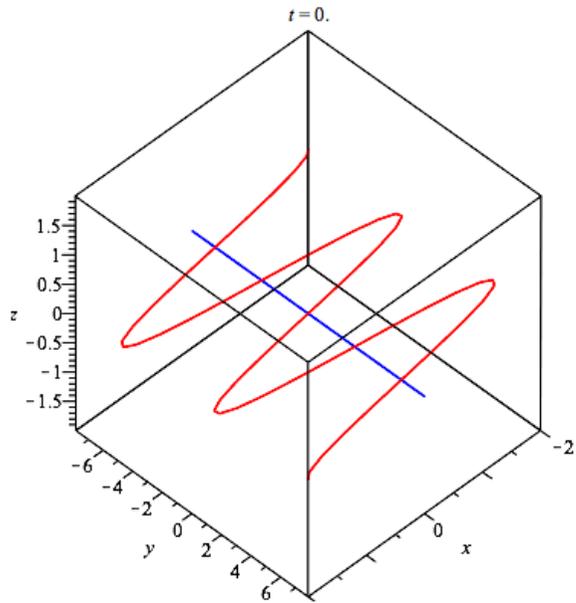


$$\rho_E(y,t)$$

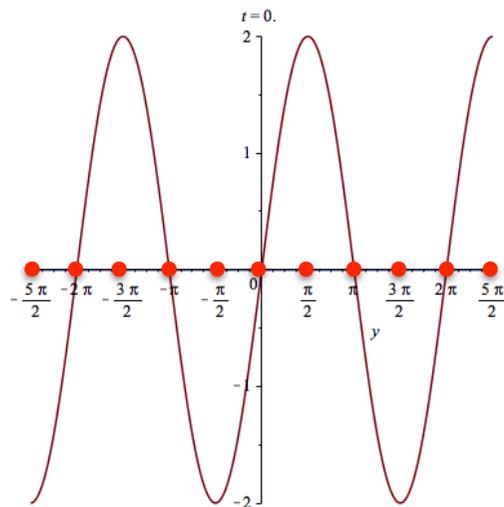


$$j_{E,y}(y,t)$$

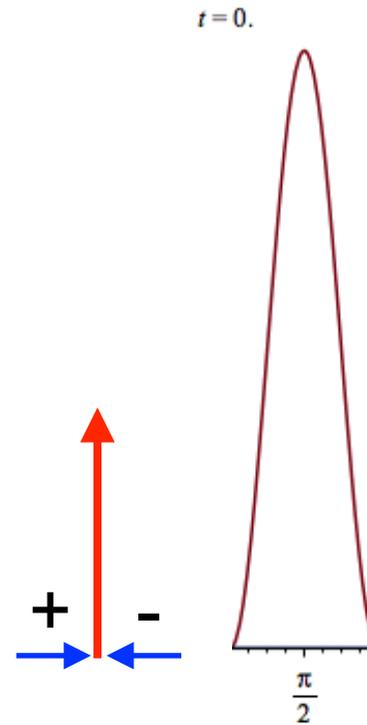
# B stehende elektromagnetische Welle



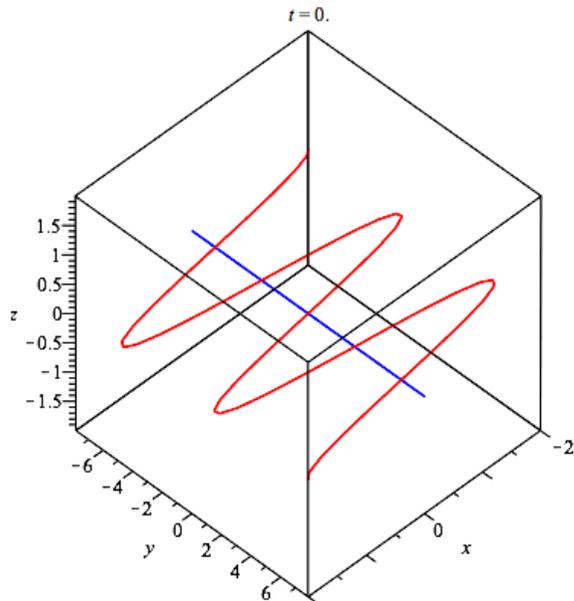
$$\rho_E(y,t)$$



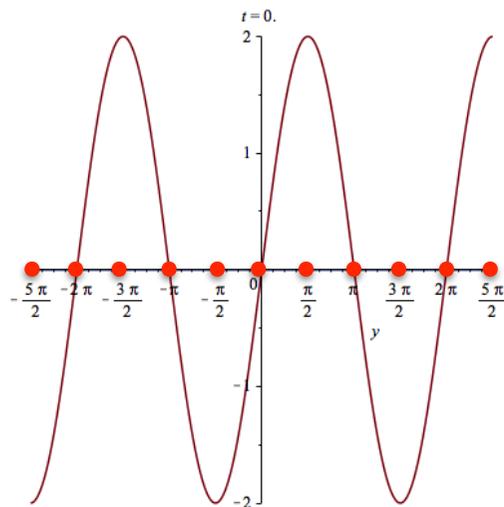
$$j_{E,y}(y,t)$$



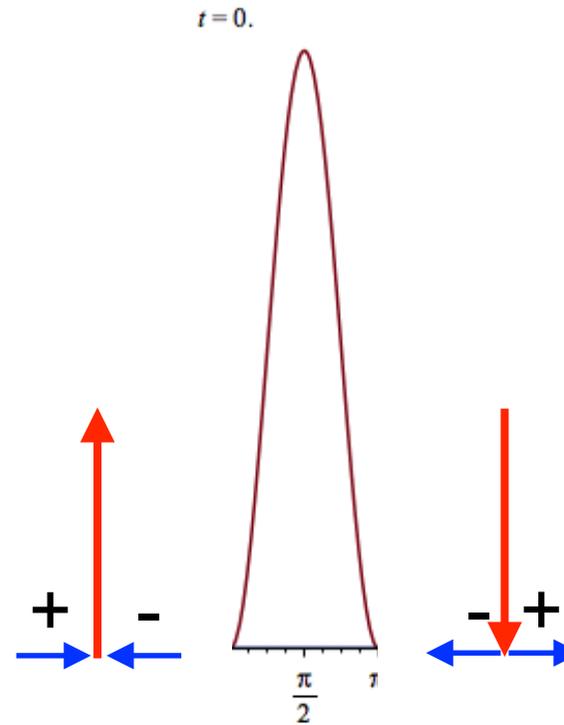
# B stehende elektromagnetische Welle



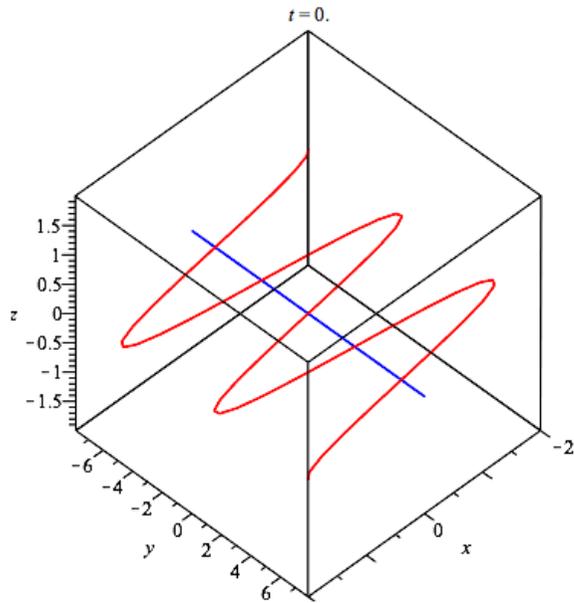
$$\rho_E(y,t)$$



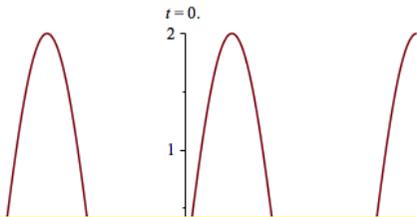
$$j_{E,y}(y,t)$$



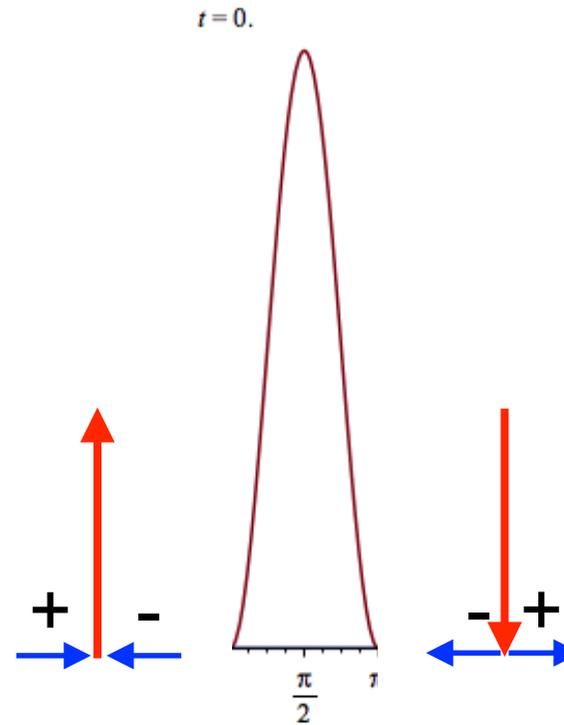
# B stehende elektromagnetische Welle



$$\rho_E(y,t)$$



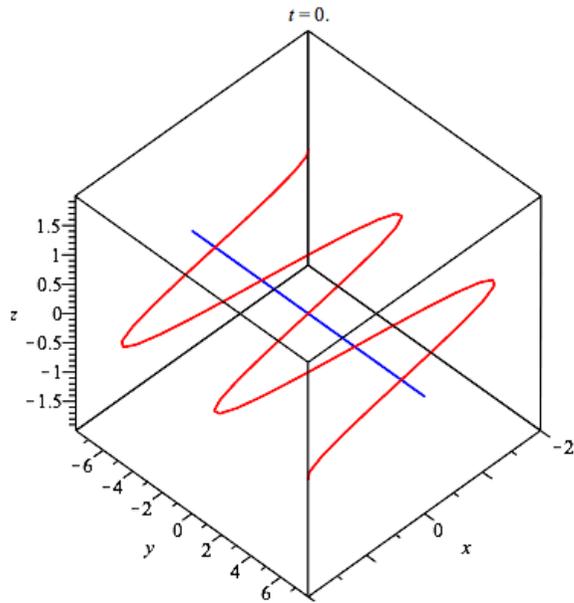
$$j_{E,y}(y,t)$$



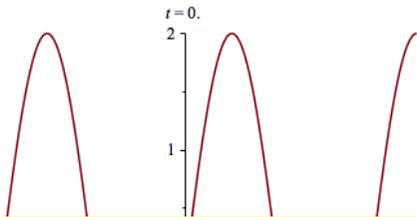
stehende elektromagnetische Welle:

- **Energiewechselströme** (kein Netto-Energietransport)
- **Impulsstrom** (?)

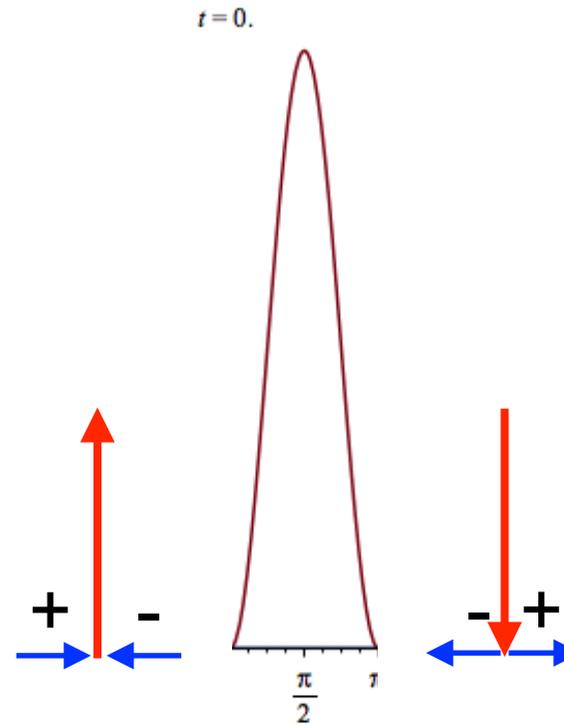
# B stehende elektromagnetische Welle



$$\rho_E(y,t)$$



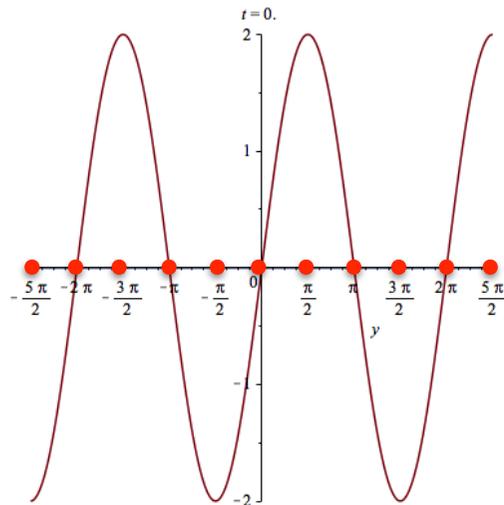
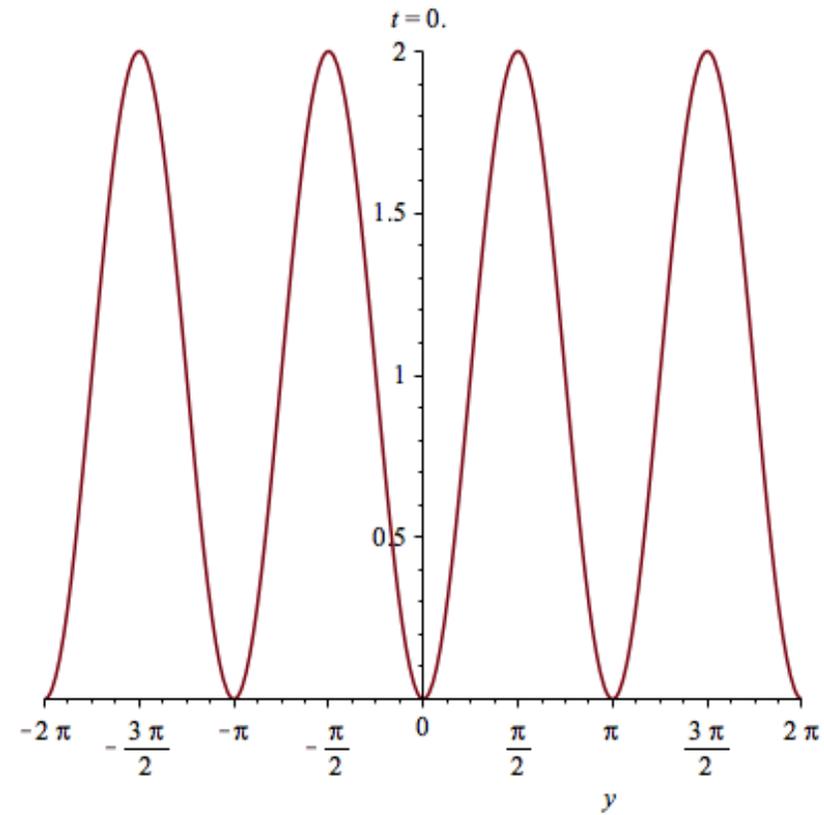
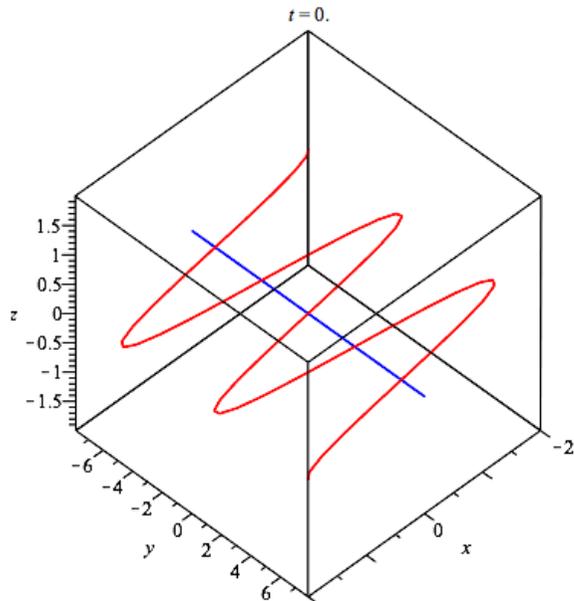
$$j_{E,y}(y,t)$$



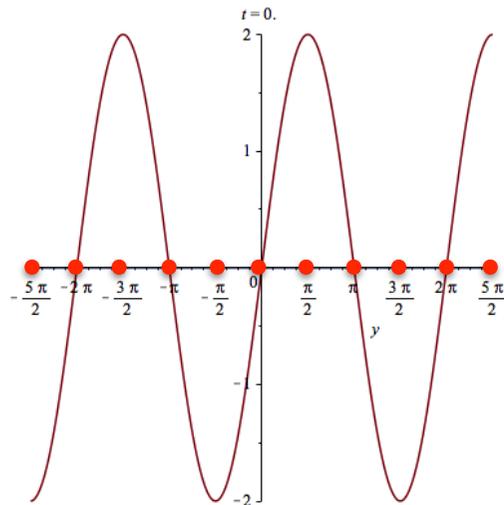
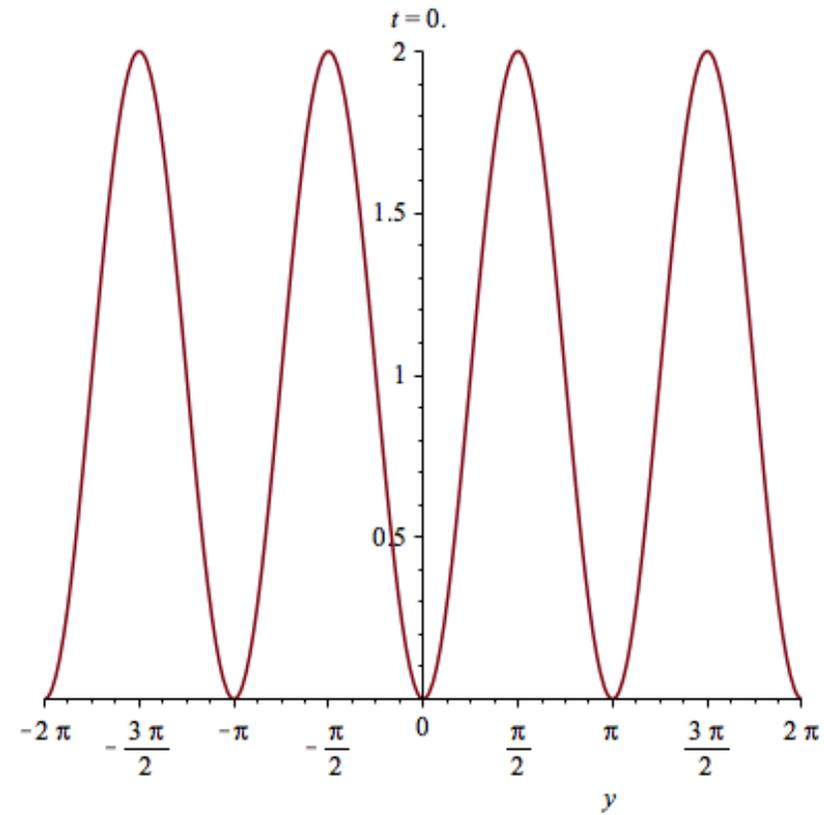
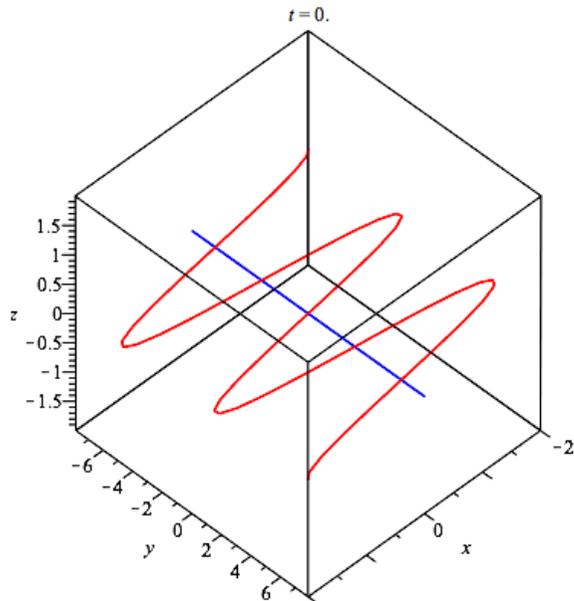
stehende elektromagnetische Welle:

- **Energiewechselströme** (kein Netto-Energietransport)
- **Impulsstrom** (?)

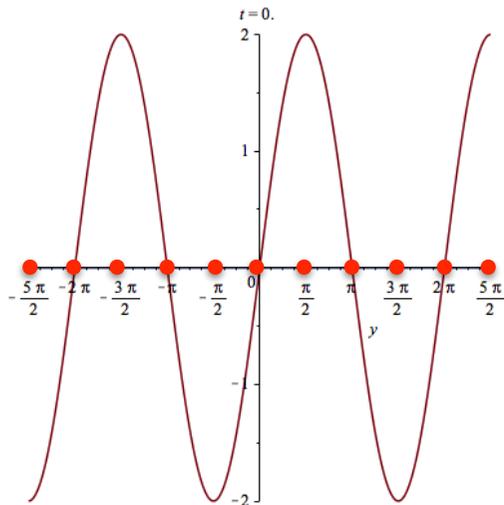
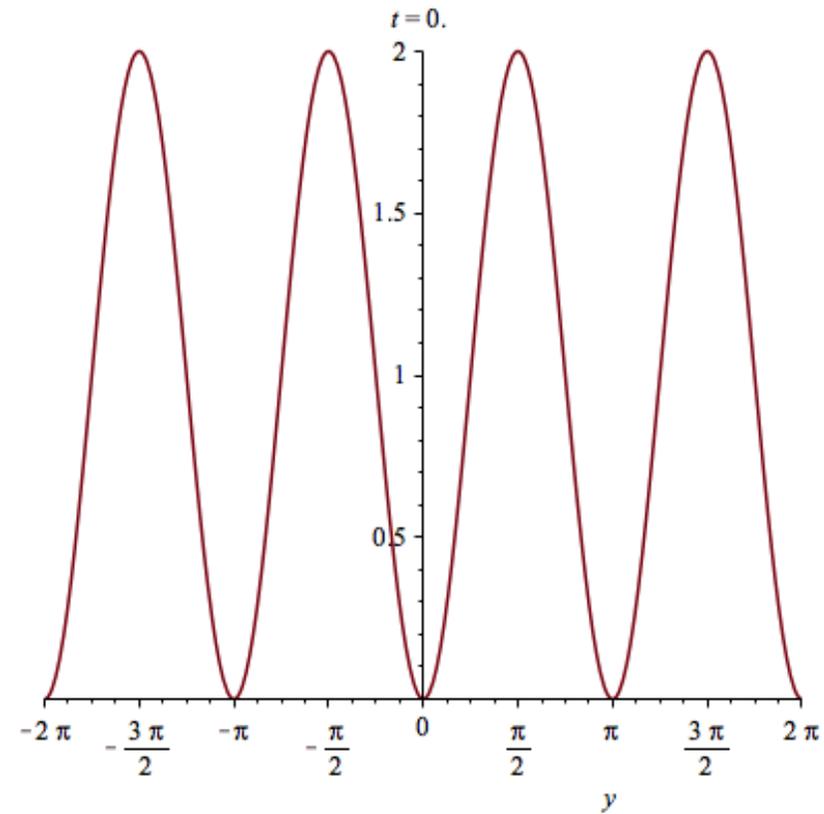
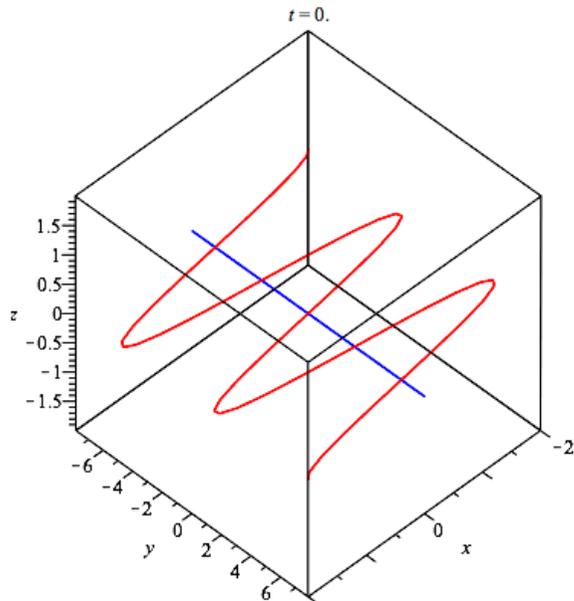
# B stehende elektromagnetische Welle



# B stehende elektromagnetische Welle



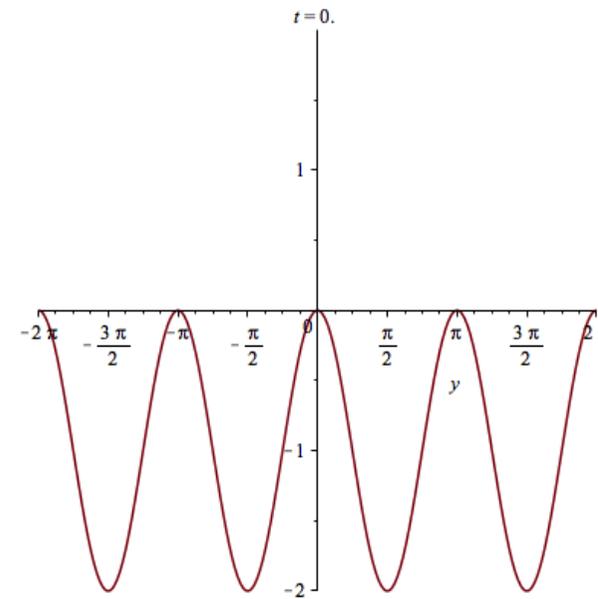
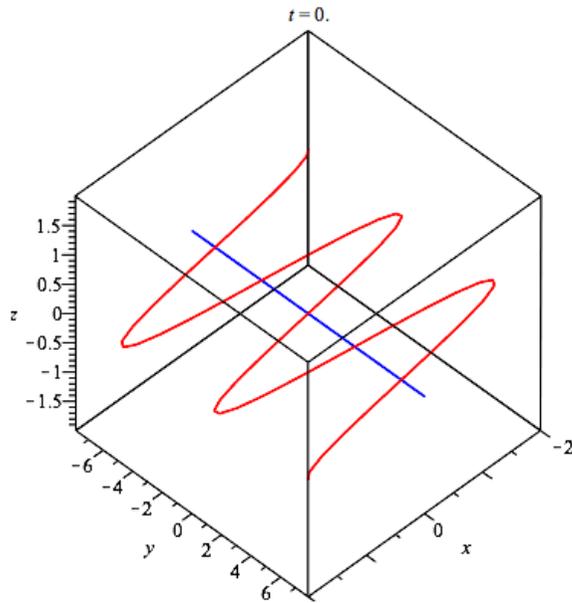
# B stehende elektromagnetische Welle



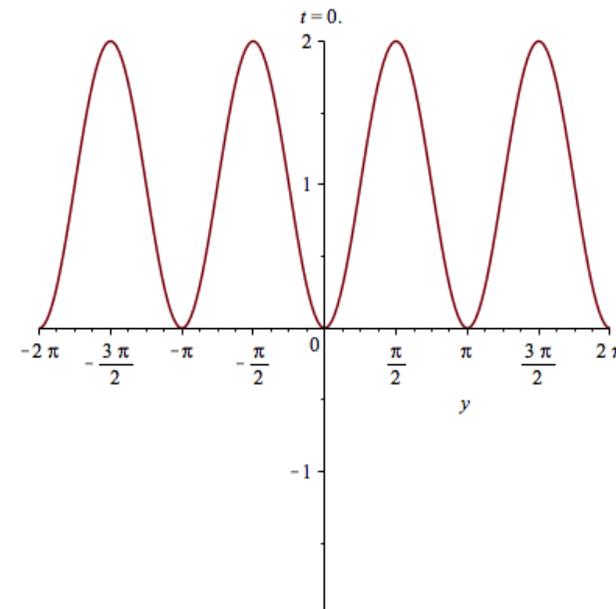
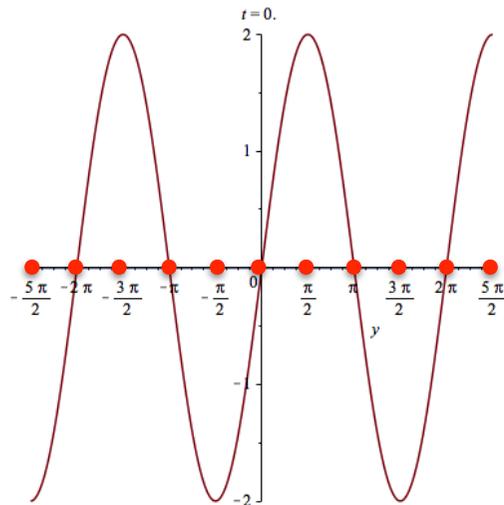
**$y$ -Impuls strömt pulsierend  
nur in positive  $y$ -Richtung  
(positiver Netto-Transport)**

# B stehende elektromagnetische Welle

**z-Impulsstrom in z-Richtung**

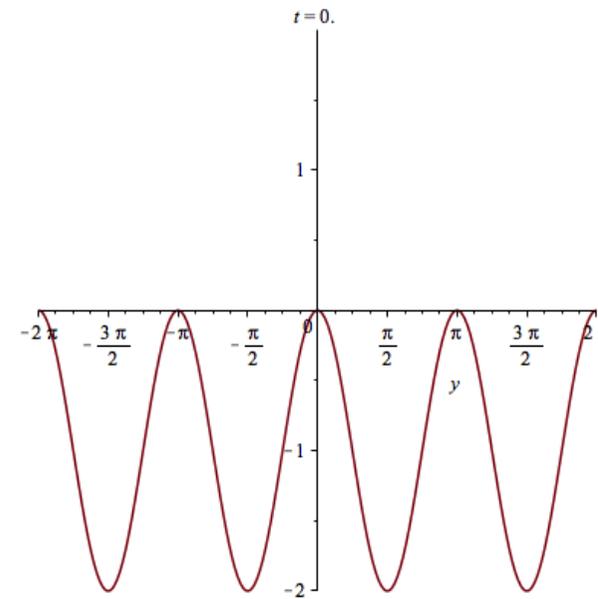
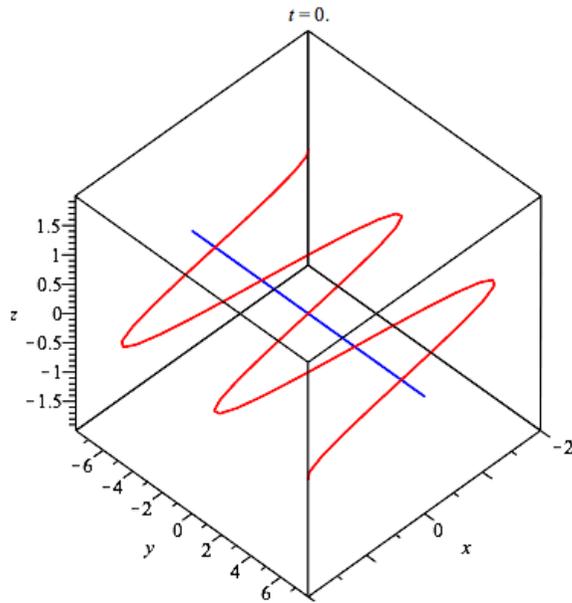


**x-Impulsstrom in x-Richtung**

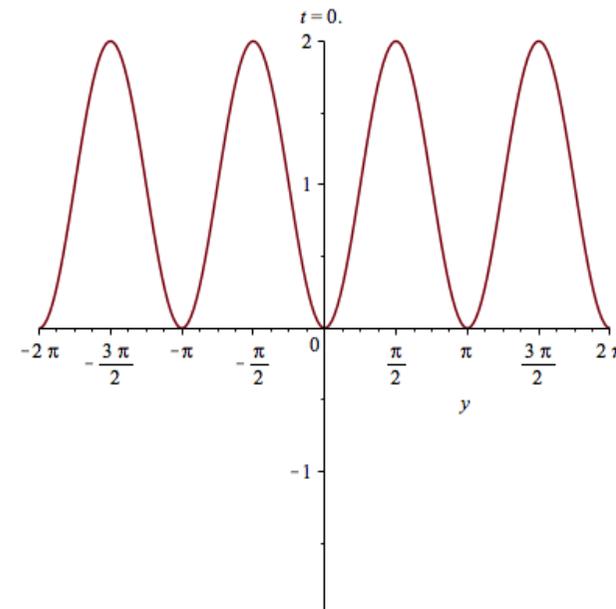
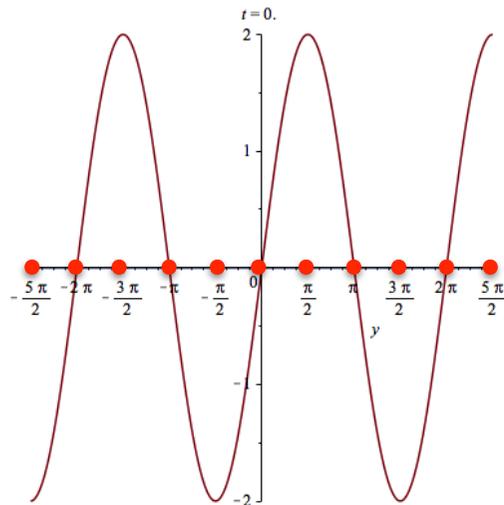


# B stehende elektromagnetische Welle

**z-Impulsstrom in z-Richtung**

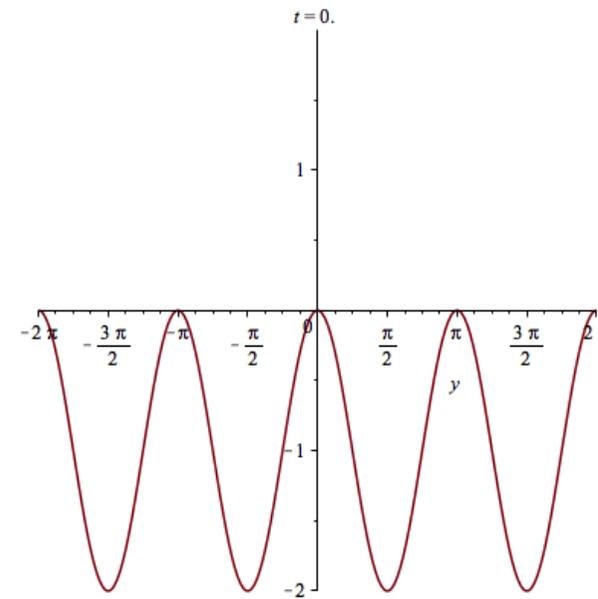
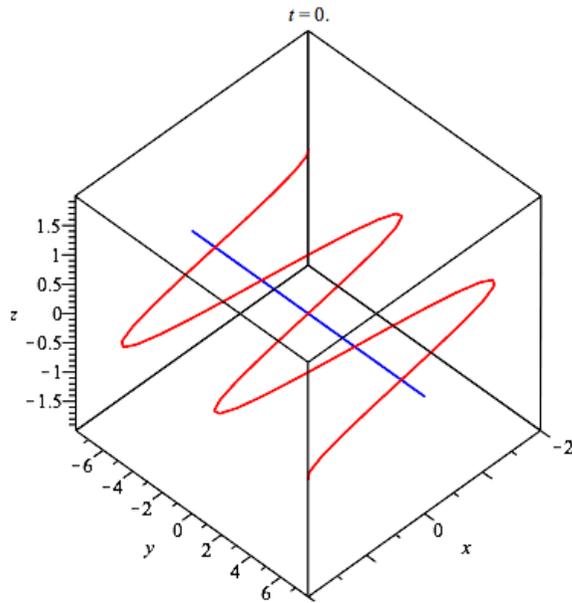


**x-Impulsstrom in x-Richtung**

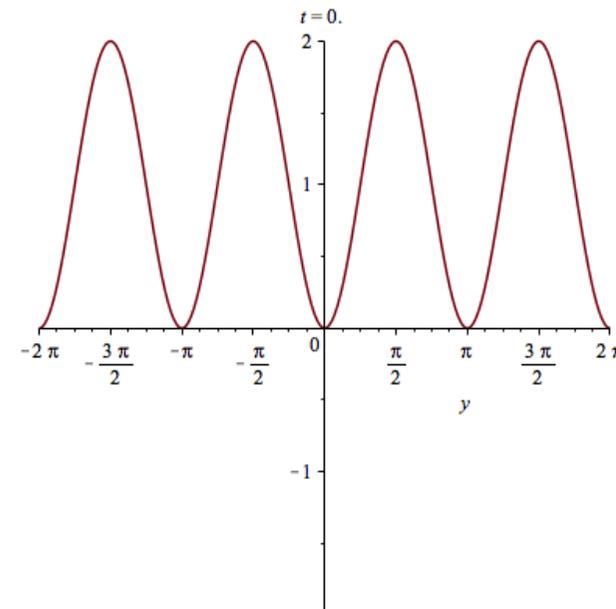
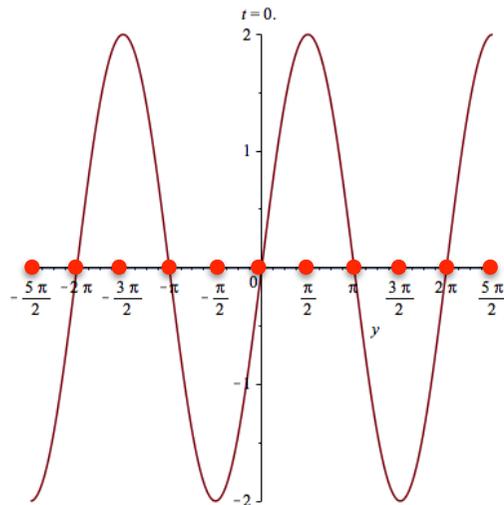


# B stehende elektromagnetische Welle

**z-Impulsstrom in z-Richtung**

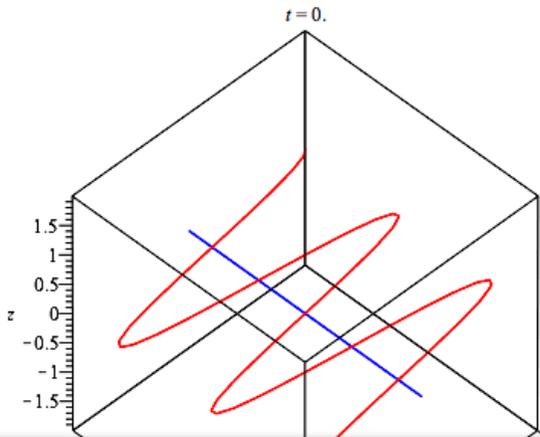


**x-Impulsstrom in x-Richtung**

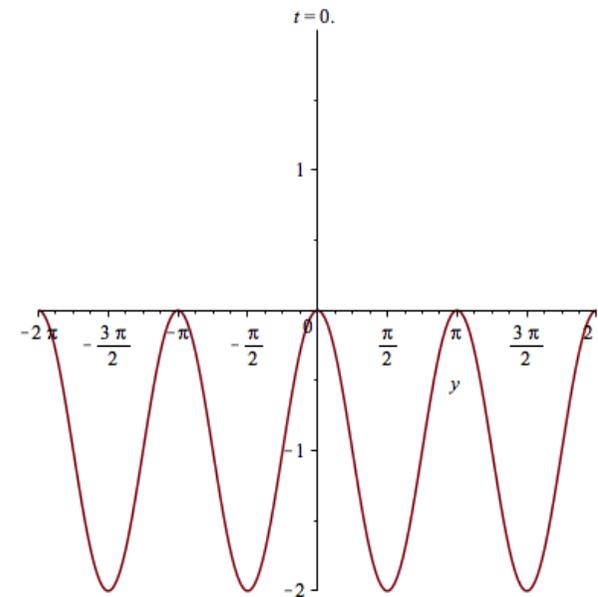


# B stehende elektromagnetische Welle

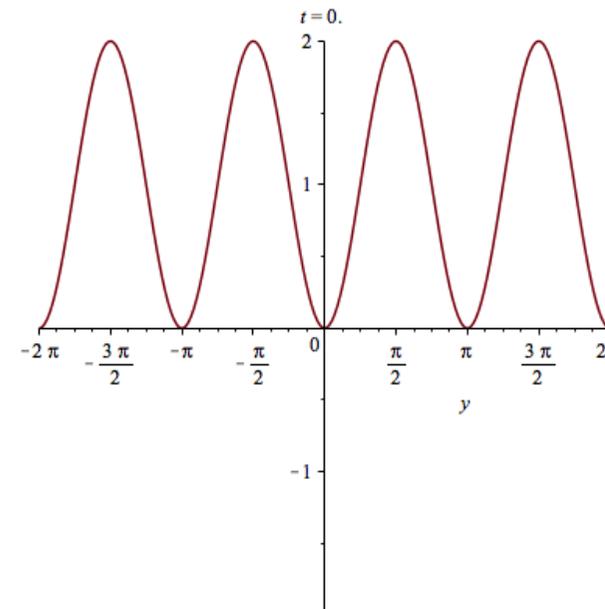
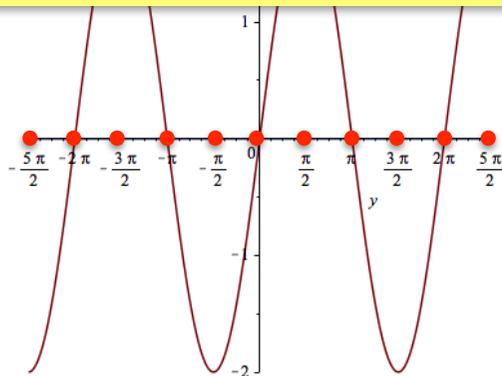
**z-Impulsstrom in z-Richtung**



**x- und z- Impuls strömen  
pulsierend nur in x- bzw. z-  
Richtung (kein Netto-  
Transport)**

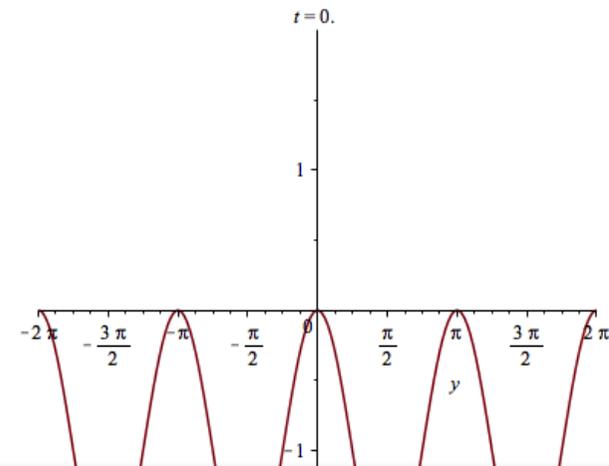


**x-Impulsstrom in x-Richtung**

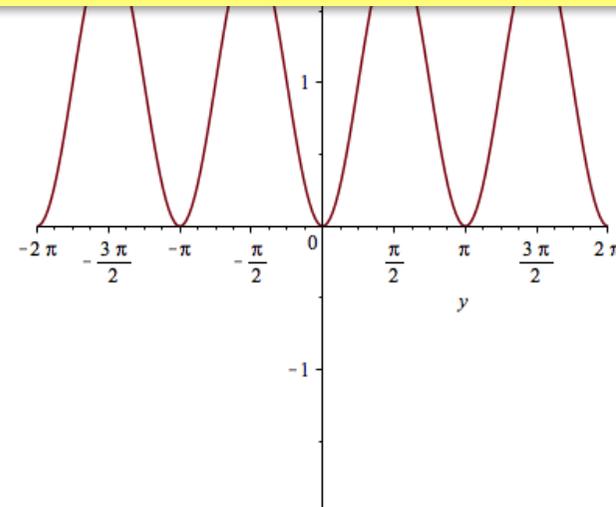


# B stehende elektromagnetische Welle

$z$ -Impulsstrom in  $z$ -Richtung

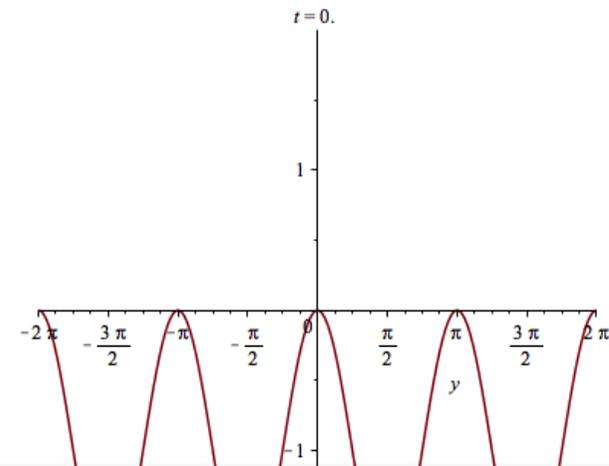


$x$ - und  $z$ - Impuls strömen  
pulsierend nur in  $x$ - bzw.  $z$ -  
Richtung (kein Netto-  
Transport)

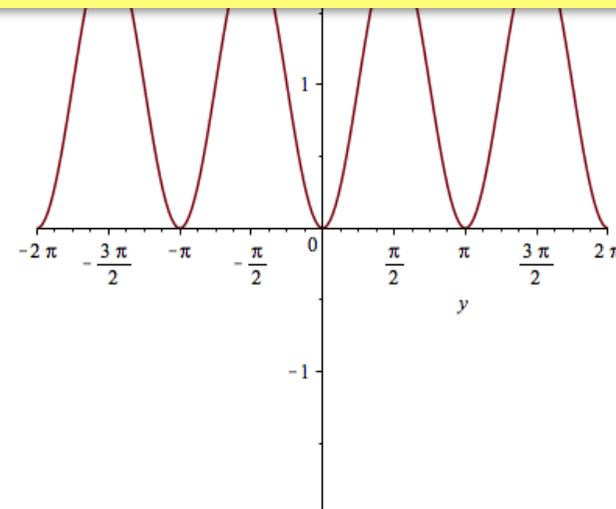


# B stehende elektromagnetische Welle

$z$ -Impulsstrom in  $z$ -Richtung



$x$ - und  $z$ - Impuls strömen  
pulsierend nur in  $x$ - bzw.  $z$ -  
Richtung (kein Netto-  
Transport)



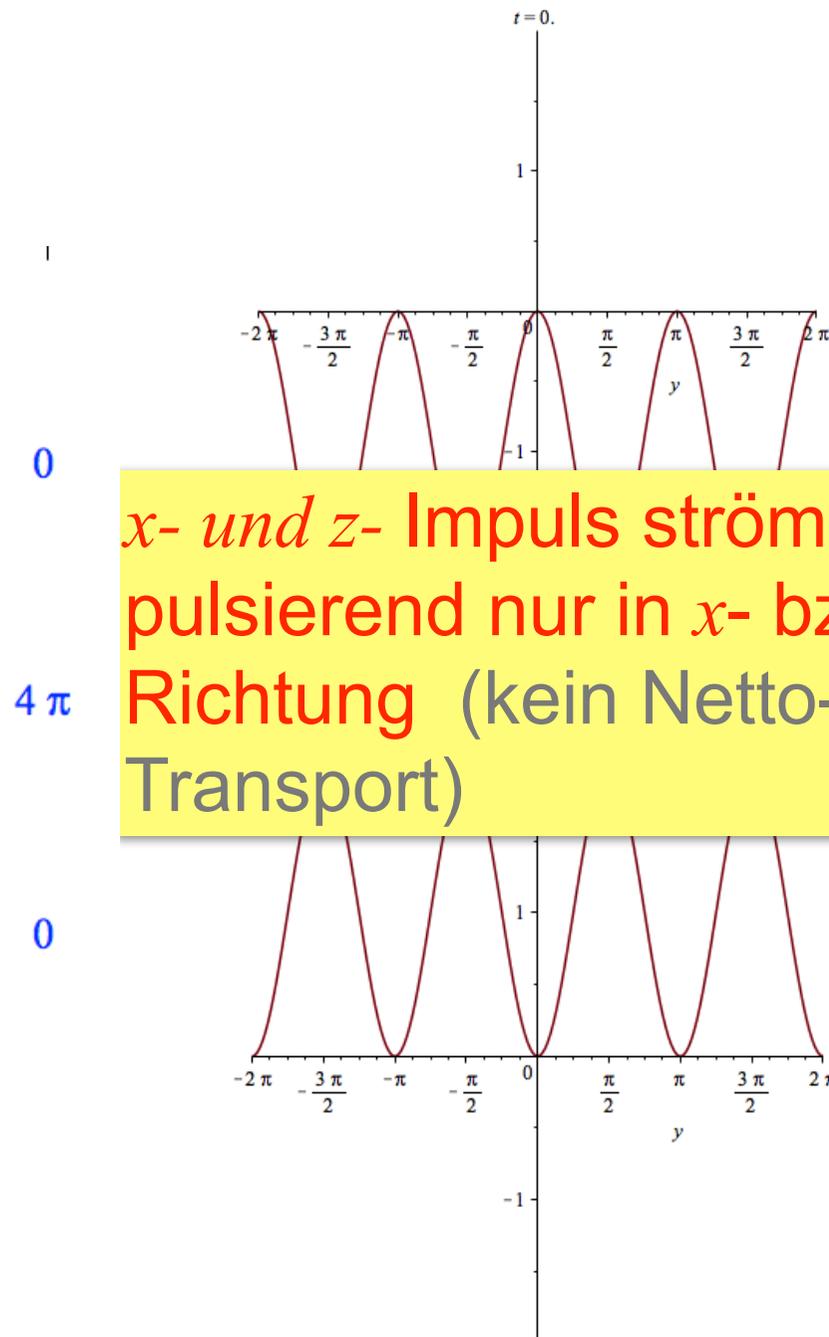
# B stehende elektromagnetische Welle

*z*-Impulsstrom in *z*-Richtung

$$\frac{1}{2\pi} \int_0^{2\pi} \left( \int_{-2\pi}^{2\pi} -\sigma_{xx} dy \right) dt$$

$$\frac{1}{2\pi} \int_0^{2\pi} \left( \int_{-2\pi}^{2\pi} -\sigma_{yy} dy \right) dt$$

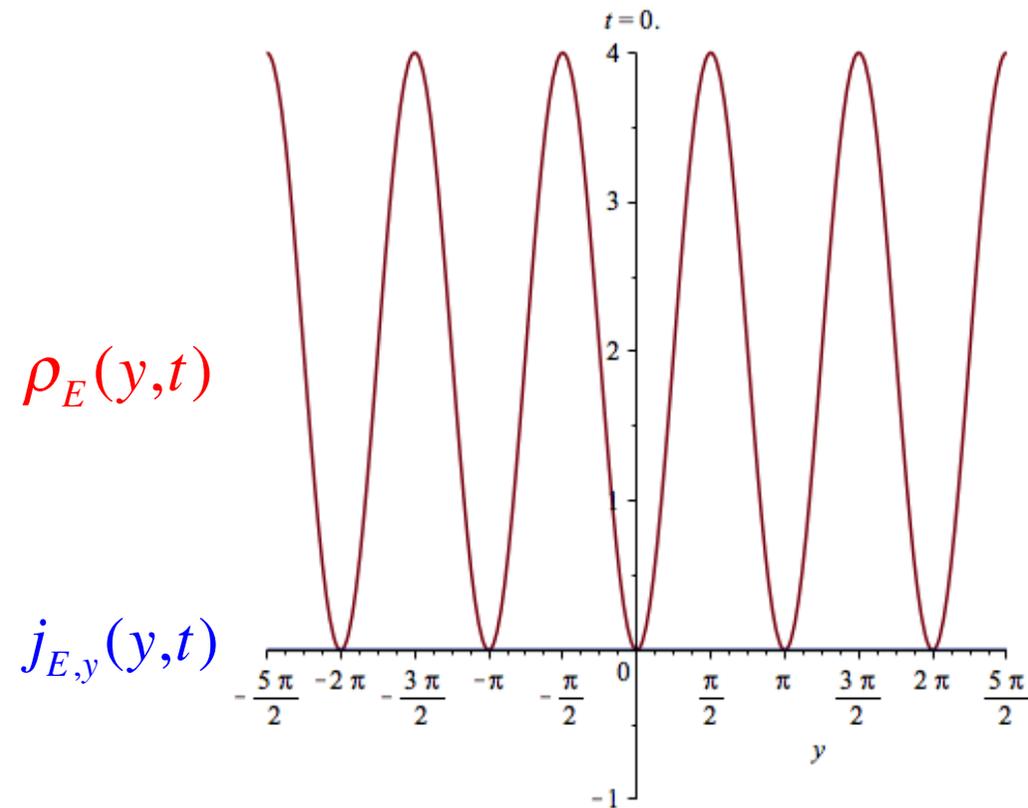
$$\frac{1}{2\pi} \int_0^{2\pi} \left( \int_{-2\pi}^{2\pi} -\sigma_{zz} dy \right) dt$$



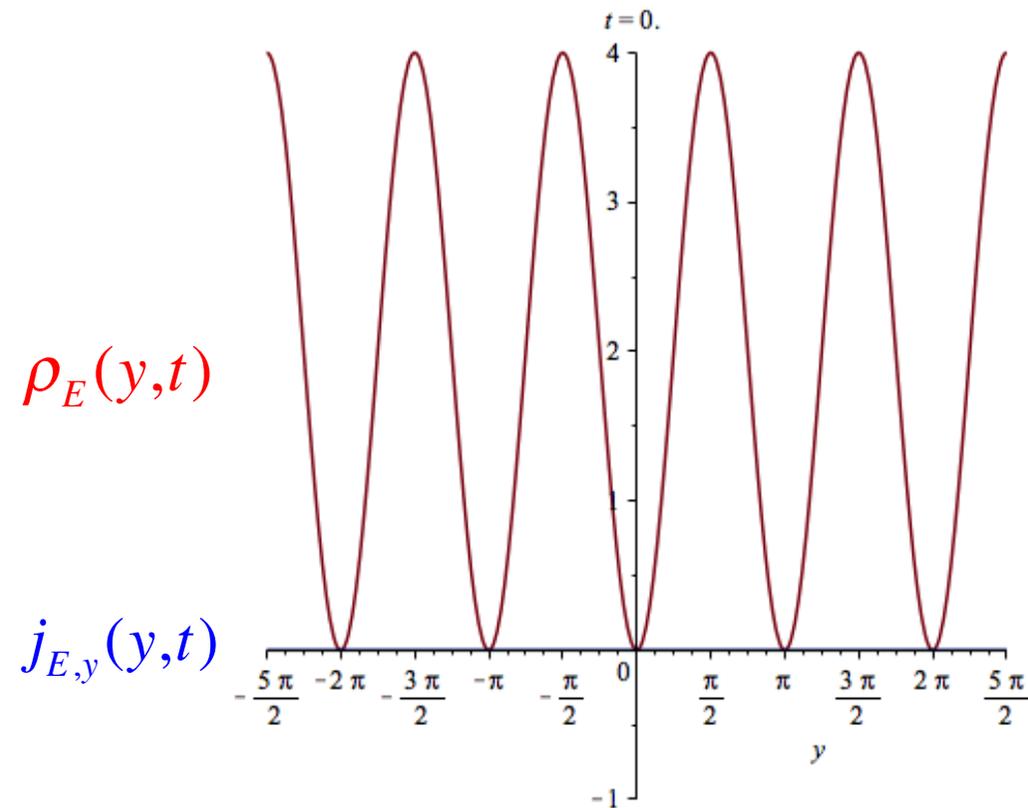
# B stehende elektromagnetische Welle

$$\sigma_{i,j} = \begin{pmatrix} 2 \cdot \sin(y)^2 \cdot \cos(t)^2 - 2 \cdot \cos(y)^2 \cdot \sin(t)^2 & 0 & 0 \\ 0 & -\frac{1}{2} \cdot (-\sin(-y+t) - \sin(y+t))^2 - \frac{1}{2} \cdot (-\sin(-y+t) + \sin(y+t))^2 & 0 \\ 0 & 0 & 2 \cdot \cos(y)^2 \cdot \sin(t)^2 - 2 \cdot \sin(y)^2 \cdot \cos(t)^2 \end{pmatrix}$$

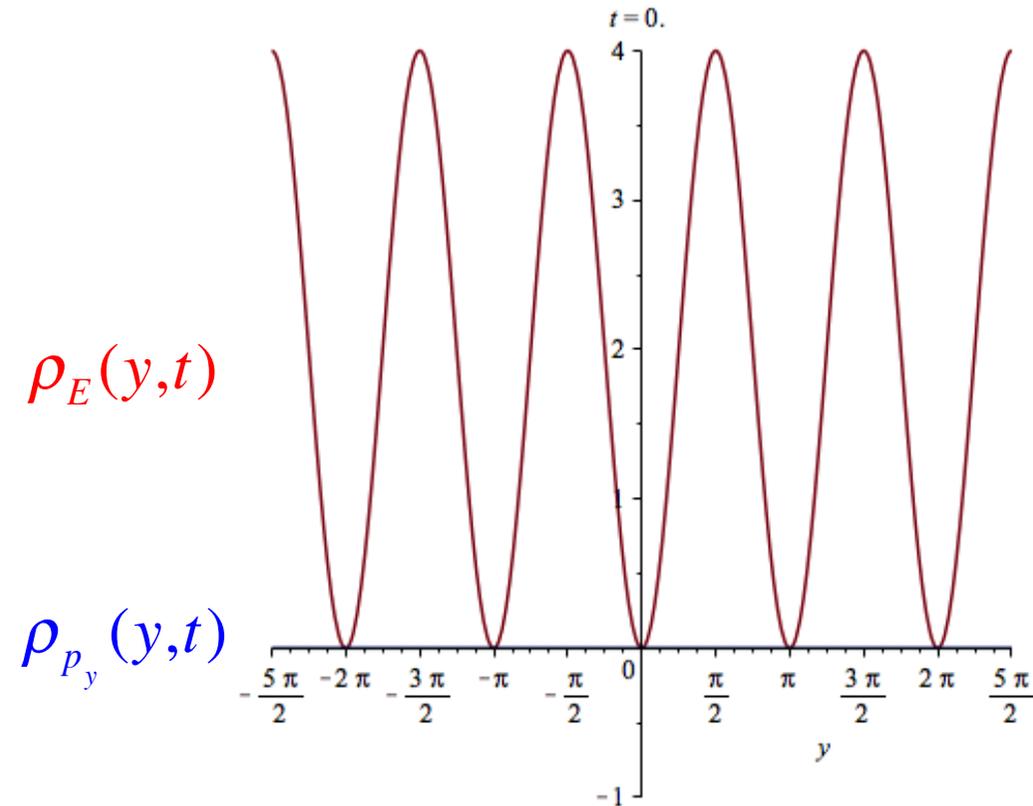
# B stehende elektromagnetische Welle

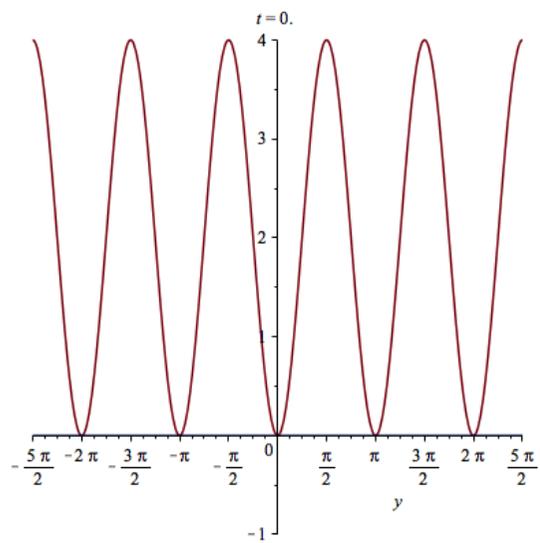


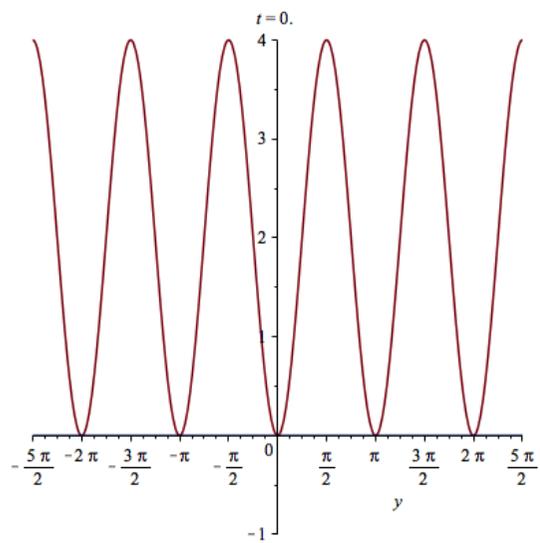
# B stehende elektromagnetische Welle



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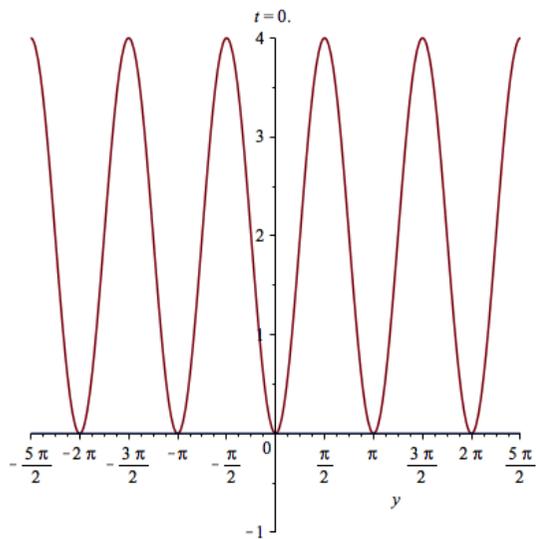


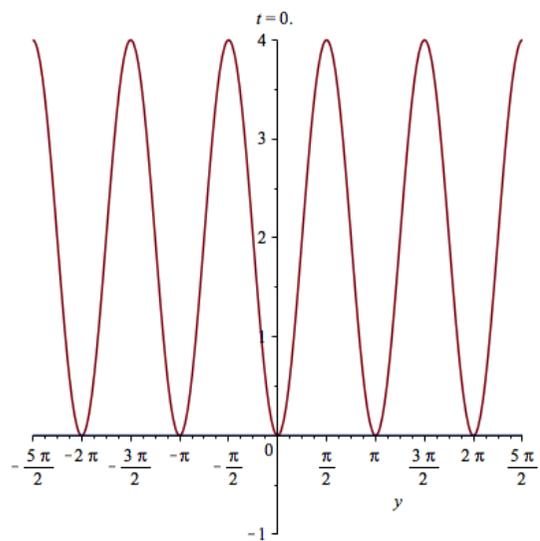




$$\rho_E(y,t)$$

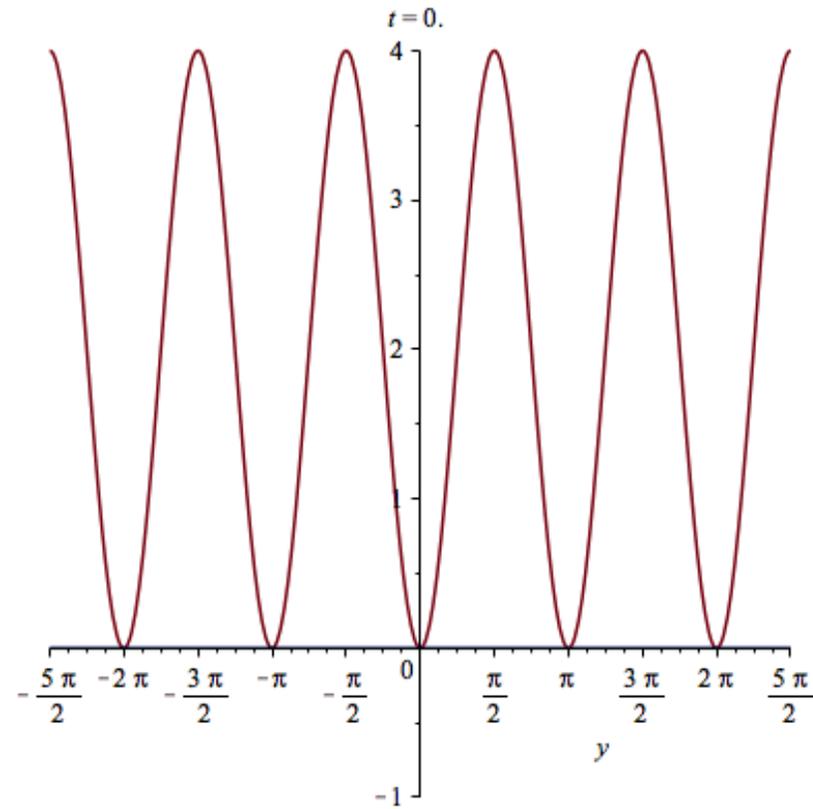
$$\rho_{p_y}(y,t)$$





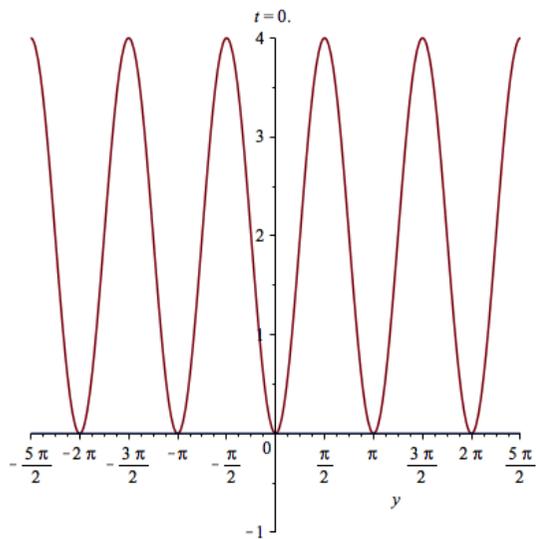
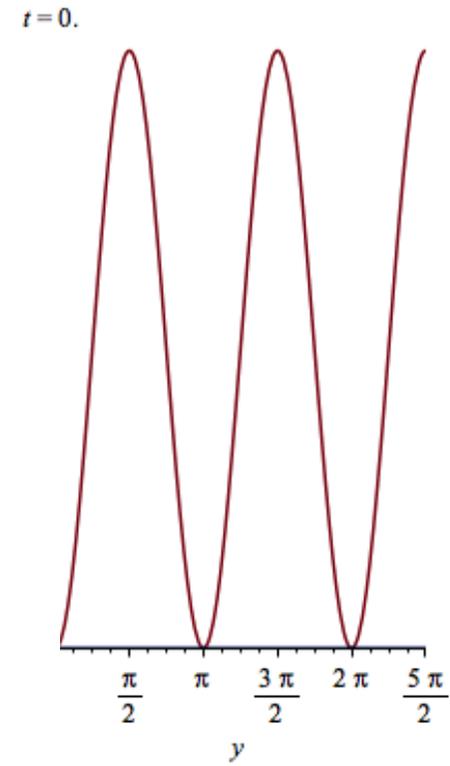
$$\rho_E(y,t)$$

$$\rho_{p_y}(y,t)$$



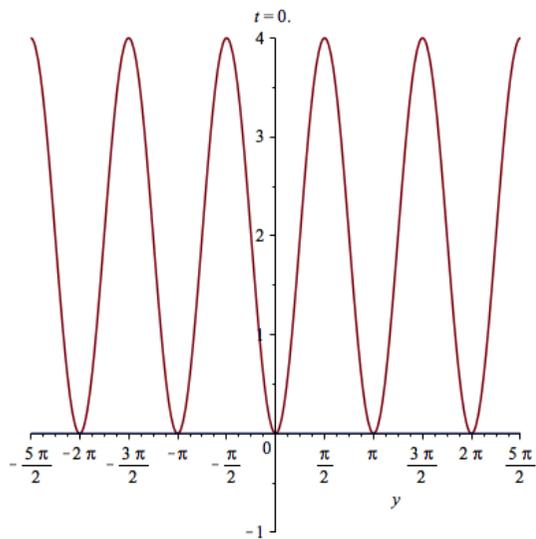
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$$\rho_E(y,t)$$

$$\rho_{p_y}(y,t)$$



Das war's