Magnetic Field of a Rotating Charged <u>Conducting</u> Sphere

#### 2<sup>nd</sup> version: on-axis and off-axis

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# Presentations:

- Electromagnetism: History
- Electromagnetism: Electr. topics
- Electromagnetism: Magn. topics
- Electromagnetism: Waves topics
- Capacitor filling (complete)
- Capacitor filling (partial)
- Divergence Theorem
- E-field of a thin long charged wire
- E-field of a charged disk
- E-field of a dipole
- E-field of a line of dipoles
- E-field of a charged sphere
- E-field of a polarized object

- E-field: field energy
- Electromagnetism: integrations
- Electromagnetism: integration elements
- Gauss' Law for a cylindrical charge
- Gauss' Law for a charged plane
- Laplace's and Poisson's Law
- B-field of a thin long wire carrying a current
- B-field of a conducting charged sphere
- B-field of a homogeneously charged sphere

Presentations and programs (free) can be downloaded from: www.demul.net/frits

# **B**-field of a rotating charged <u>conducting</u> sphere

#### Available:



A charged conducting sphere (charge Q, radius R), rotating with  $\omega$  rad/sec

Question:

Calculate *B*-field in arbitrary points inside and outside the sphere

- I. on the axis of rotation
- II. off-axis

Ad. I : analytical approach possible Ad. II : numerical approach needed B -FIELD OF A SPHERE OR SPHERE SEGMENT --- XY-plane at Z=0. Modulus of B, normalised on B in O (= 1.33371E-06 T)

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**Objective:** 

B-field: of a charged conductive sphere rotating around the X-axis

Inside the sphere: homogeneous field 4

# Analysis and Symmetry for on-axis (1)



Assume P on Z-axis.

Part I. Calculate *B*-field in point *P* 

on the axis of rotation (Z-axis)

inside or outside the sphere

(Part II: points P off-axis)

Coordinate systems:

- X,Y, Z
- r, θ, φ

Symmetry: around rotation axis.

# Analysis and Symmetry for on-axis (2)



<u>Conducting sphere</u>, all charges at surface: surface charge density:  $\sigma = Q/(4\pi R^2)$  [C/m<sup>2</sup>]

Rotating charges will establish a "surface current",

directed along surface circles.

Surface current density *j*' [A/m]:

will be a function of  $\theta$ 

B-field of a rotating charger commence of the second secon

### Analysis and Symmetry for on-axis (3)



 $\boldsymbol{dB} = \frac{\mu_0}{4\pi} \frac{I.\,\boldsymbol{dl} \times \boldsymbol{e_r}}{r_P^2}$  $dB \perp dl$  and  $e_r$ . if P = on-axis:  $dl \perp e_r$ 

Direction of *dB*:

Cylindrical symmetry around Z-axis:

Z-comp. only !! X- and Y-comp.

## Analysis and Symmetry for on-axis (4)



### Intermezzo: a surface current



## Analysis and Symmetry for on-axis (4)



Biot & Savart :

$$\mathbf{dB} = \frac{\mu_0}{4\pi} \frac{\mathbf{j}' db. dl \times \mathbf{e_r}}{{r_P}^2} = \frac{\mu_0}{4\pi} \frac{\mathbf{j}' \times \mathbf{e_r}}{{r_P}^2} dA$$

dB, dl and  $e_r$ mutually perpendicular

> Needed: expressions for: dA, j',  $e_r$ ,  $r_P$





### Conducting sphere: on-axis (3)

d₩

 $d\phi$ 

B-field of a rotating cl

 $R.\sin\theta.d\phi$ 

 $R.d\ell$ 

Ζ

 $R\sin\theta$ 



 $\frac{\text{Ring on surface}}{2\pi (R.\sin\theta).(Rd\theta)}$ 

 $\frac{\text{Charge on ring}}{\sigma}: 2\pi R.\sin\theta \cdot Rd\theta$ 

Full rotation over  $2\pi$  in  $2\pi/\omega$  s.

current:  $dI = \sigma . 2\pi R . \sin \theta . R d\theta / (2\pi/\omega)$ =  $\sigma \omega R \sin \theta . R d\theta$ 

<u>current density</u>:  $j' = dI / (Rd\theta) =$ 







#### Conducting sphere: on-axis (7)



#### Conducting sphere: on-axis (8)

$$B_{Z} = \int_{0}^{2\pi} d\varphi \int_{0}^{\pi} d\theta \frac{\mu_{0}}{4\pi} \frac{\sigma \omega R^{4} \sin^{3} \theta}{r_{P}^{3}} \quad \text{with:} \\ r_{P}^{2} = (R.\sin\theta)^{2} + (z_{P} - R.\cos\theta)^{2}$$

Set: 
$$\frac{z_P}{R} = q$$
, and:  $\cos \theta = x$ , and with  $a = 1 + q^2$  and  $b = -2q$ :  
 $B_z = \int_{-1}^{+1} \frac{x^2 - 1}{(a + bx)^{3/2}} dx = \frac{8}{3b^3} \left[ (b - 2a)\sqrt{a + b} + (b + 2a)\sqrt{a - b} \right]$ 

(Set a+bx = y, and express dx and  $x^2-1$  in dy and y, and integrate...)

4 solutions, depending on  $\sqrt{(..)}$ -terms:

1. 
$$z_P \leq -R$$
  
2.  $-R \leq z_P \leq 0$   
3.  $0 \leq z_P \leq R$   
4.  $z_P \geq R$ 

 $\begin{array}{c} 4 \\ \hline 3 \\ \hline 2 \\ \hline 1 \\ \end{array}$ 

#### Conducting sphere: on-axis (9)



result : 
$$\mathbf{B}_{p} = \frac{2\mu_{0}\sigma\omega R^{4}}{3.z_{p}^{3}}\mathbf{e}_{z}$$

this result holds for  $z_P > R$ ;

for  $-R < z_P < R$  the result is:

$$\mathbf{B}_{P} = \frac{2}{3} \,\mu_0 \boldsymbol{\sigma} \boldsymbol{\omega} \boldsymbol{R} \, \mathbf{e}_{\mathbf{z}}$$

and for 
$$z_P < -R$$
:  $\mathbf{B}_P = \frac{2\mu_0 \sigma \omega R^4}{-3.z_p^3} \mathbf{e}_z$ 

**B** directed along  $+e_z$  for all points everywhere on Z-axis !!

inside sphere: constant field !!



Conclusion: inside conducting sphere: **on-axis**: field = constant.

Question: what about the field inside the sphere, but off-axis?

To be investigated in part II ==>

Conclusions for on-axis (1)

#### Conducting sphere

$$|z_{p}/ > R \qquad |z_{p}/ < R$$
$$\boldsymbol{B} = \frac{\mu_{0}Q\omega R^{2}}{6\pi |z_{p}^{3}|} \boldsymbol{e}_{z} \qquad \boldsymbol{B} = \frac{\mu_{0}Q\omega}{6\pi R} \boldsymbol{e}_{z}$$

$$Q = \sigma.4\pi R^2$$

Homogeneously charged sphere

(see other presentation)

 $|z_P| > R$ 

$$|z_P| < R$$

$$\boldsymbol{B} = \frac{\mu_0 Q \omega R^2}{10 \pi \left| z_P^3 \right|} \boldsymbol{e}_z$$

 $\boldsymbol{B} = \frac{\mu_0 Q \omega}{20 \pi R^3} \left( 5R^2 - 3z_P^2 \right) \boldsymbol{e}_z$ 

# Conclusions for on-axis (2)





Part II. Calculate **B**-field in point P off the axis of rotation (Z-axis) inside or outside the sphere

Rotation axis (Z-axis) =

= symmetry axis.

Assume P (0,  $y_P$ ,  $z_P$ ) in YZ-plane.

Coordinate systems:

### Conducting sphere: off-axis (1)



#### Conducting sphere: off-axis (2)



#### Conducting sphere: off-axis (2)



#### Conducting sphere: off-axis (4)

Available for download on <u>www.demul.net/frits</u>: offline program: EM\_solenoids in file: EM\_programs.zzz on subpage Electromagnetism

This program can calculate:

- **B-** and **A**-fields for:
- Single solenoids
- Pairs of solenoids
  - Dipole fields
- Field of a rotating charged conducting sphere
  - and sphere segments



#### 1. Rotating charged conducting sphere

**Properties:** 

- Charge = 1 C
- Radius = 5 cm
- Velocity = 1 rad/s = 0.1592 rev./s
- NB. Rotation axis = symmetry axis = X-axis; Fields shown in XY-plane at Z=0.



#### 1. Rotating charged conducting sphere: settings:

#### Options

- Single solenoid
- Pair of solenoids
- O Dipolar far-field approximation
- Conducting sphere or sphere segment

#### Field pattern

- B : Field line vectors
- B : Modulus, values
- B : Modulus, squares
- B : X-components, values
- B : X-components, squares
- B : Y-components, values
- B : Y-components, squares
- A : Z-components, values
- A : Z-components, squares

X-axis =	rotation	(symme	etry) a	xis											
Sphere r	adius nter in C	)	5.0	0											
Charge		1.0	1.000E+00												
Charge d segment	Charge density on sphere/ segment: 3.183E+01 C/m^2														
Rotation [revolution	Rotation velocity [revolutions/sec]														
Idem : 1	.000E+	00 rad/s	5												
Current of plane (X=	lensity a =0): 1.	at YZ-eq 592E+00	uator ) A/m												
Polar ang	le [deg]	:													
min:	0.00	max:	180.	00											
Angular i on spher	nterval e [deg]		2.0	0											
Plot dimensi	ons [cm	1]													
X left	-10.0	X	right	10	).0										
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	B -FIELD OF A SPHERE OR SPHERE SEGMENT XY-plane at Z=0. Modulus of B, normalised on B in O (= $1.33371E-06$ T)																				
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	6	7	9	10	12	14	16	17	18	18	18	18	18	17	16	14	12	10	9	7	6
	- 7	9	11	13	16	20	23	26	28	29	29	29	28	26	23	20	16	13	11	9	7
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**B-field**: Sphere rotating around X-axis

Inside the sphere: homogeneous field

Field strength inside = 1.3337 µT

# Conducting sphere rotating around X-axis : *B* and *A*-fields

**B-field:** Cross section of sphere: XY-plane at Z=0:



Inside the sphere: Homogeneous **B**-field == > **A**-field varies linearly with y-coordinate (due to derivatives in *rot* (*curl*) Expression for a surface current:

$$dB = \frac{\mu_0}{4\pi} \frac{j' \times e_r}{r^2} dA$$

A-field: Vector potential:  $B = \operatorname{rot} A (= \operatorname{curl} A)$ 

$$dA = \frac{\mu_0}{4\pi} \frac{j'}{r} dA$$

**B** and **A** : perpendicular fields.

For points in XY-plane: *B* in XY-plane, no Z-component  $A^{\perp}$  XY-plane, Z-component only.

For points outside XY-plane: Cylindrical symmetry around X-axis.

**в-него ог а гоганид сп**arged conducting sphere

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								X-ax	is (rot	ation	symm	etry a	xis) /	cm							

**A-field:** Sphere rotating around X-axis

A = 0 at rotation symmetry axis

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2. Rotating charged conducting sphere segment between 45<sup>0</sup> and 135<sup>0</sup> (ring shape)

Properties:

- Charge = 1 C
- Radius = 5 cm
- Velocity = 1 rad/s = 0.1592 rev./s



**B-field**: Sphere segment (ring shape) rotating around X-axis

Field already looks like a solenoid field

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6	7 8	10	12	15	17	19	20	20	20	20	20	19	17	15	12	10	8	7	6
- 7	8 10	13	16	21	26	30	32	33	33	33	32	30	26	21	16	13	10	8	7
8 1	10 13	16	22	29	40	50	56	_ <b>52</b> .	-28-	-52_	56	50	40	29	22	16	13	10	8
- 9 1	11 15	20	27	40	64	90	111	110	110	110	111	90	64	40	27	20	15	11	9
10 1	13 17	23	32	47	75	102	105	106	107	106	105	102	75	47	32	23	17	13	10
- 10 1	14 18	25	35	50/	70	88	98	102	103	102	98	88	70	50	35	25	18	14	10
11 1	14 19	26	36	50	67	83	94	99	101	99	94	83	67	\ 50	36	26	19	14	11
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**B-field**: Sphere segment (ring shape) rotating around X-axis

Field already looks like a solenoid field



3. Rotating charged conducting sphere segment between 120<sup>0</sup> and 180<sup>0</sup> (bowl shape)

**Properties:** 

- Charge = 1 C
- Radius = 5 cm
- Velocity = 1 rad/s = 0.1592 rev./s



**B-field**: Sphere segment (bowl shape) rotating around X-axis

Field already looks like a dipolar field

	B -FIELD OF A SPHERE OR SPHERE SEGMENT XY-plane at Z=0. Modulus of B, normalised on B in O (= $8.33341E-07 T$ )																					
10		5	6	6	7	7	7	7	7	7	7	7	6	6	5	5	4	4	3	3	3	2
10		7	7	8	, Q	10	, 10	10	10	10	, 10	Ó	Q	8	7	6	5	5	4	3	3	-
		י 8	, 10	11	13	14	15	15	15	15	10	13	12	10	, 0	8	5	5	5	4	3	3
		11	10	15	10	21	13	13	15	15	13	20	17	10	11	0	0	5	5	т И	1	у Э
		14	13	13	10	21	20	42	25	25	20	20	17	14	11	12	0	0	5	4	4	2
		14	17	21	20	52	50	45	40	40	50	50	24	10	15	12	9	,	0	5	4	4
		1/	22	29	39	51	66	85	109	99	_ 65 -	-45-	-33_		18	14	11	9	/	6	5	4
		21	29	40	56	80	11/	1//	109	205	102	64	43	30	22	1/	13	10	8	6	5	4
		25	35	51	77	121	199	368	338	216	128	80	53	36	26	19	14	11	8	7	5	4
	-	28	41	63	100	168	303/	394	308	216	141	92	61	41	29	21	\ 15	12	9	7	6	5
		31	46	71	117	207	395	378	297	216	147	98	65	44	31	22	16	12	9	7	6	5
0		-32	47	74-	124 -	-223 -	··440	373	294	216	149	100	67	45	32	22	16	12	···9···	7	6	5
		31	46	71	117	207	395	378	297	216	147	98	65	44	31	22	16 /	12	9	7	6	5
	F	28	41	63	100	168	303	394	308	216	141	92	61	41	29	21	/ 15	12	9	7	6	5
		25	35	51	77	121	199	368	338	216	128	80	53	36	26	19	14	11	8	7	5	4
	-	21	29	40	56	80	117	177	109	205	102	64	43	30	22	17	13	10	8	6	5	4
		17	22	29	39	51	66	85	109	99	65	- 45	-33	24	18	14	11	9	7	6	5	4
	-	14	17	21	26	32	38	43	46	45	38	30	24	18	15	12	9	7	6	5	4	4
		11	13	15	18	21	23	24	25	25	23	20	17	14	11	9	8	6	5	4	4	3
	-	8	10	11	13	14	15	15	15	15	15	13	12	10	9	8	6	5	5	4	3	3
		7	7	8	9	10	10	10	10	10	10	9	9	8	7	6	5	5	4	3	3	3
-10	-	5	6	6	7	7	7	7	7	7	7	7	6	6	5	5	4	4	3	3	3	2
		-10				1	-5	1				0			1	1	5			1	1	10
									X-ax	is (rot	ation	symm	etry a	XIS) /	cm							

**B-field**: Sphere segment (bowl shape) rotating around X-axis

Field already looks like a dipolar field

