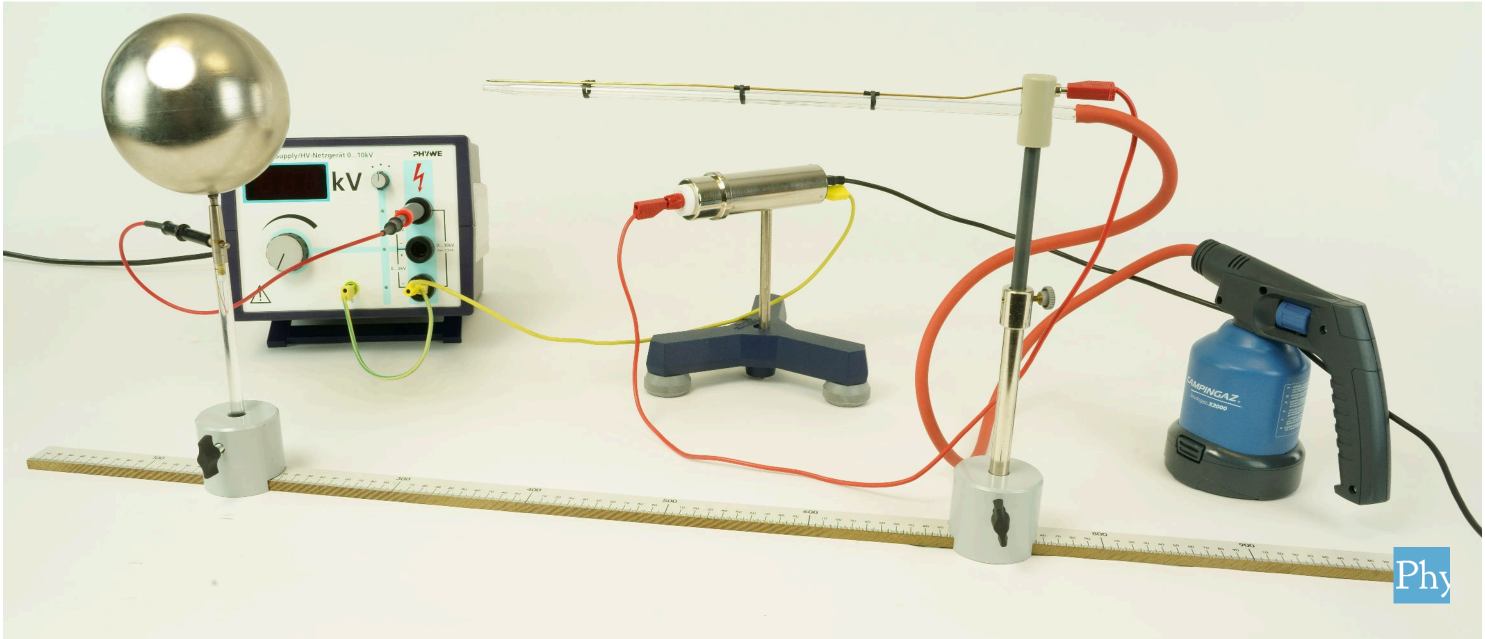
Coulomb potential and Coulomb field of metal spheres



Coulomb potential and Coulomb field of metal spheres as a function of position and voltage

Physics	Electricity & Magnetism	Electrostatics & electric field	
Difficulty level	Group size	Preparation time	Execution time
hard	2	45+ minutes	45+ minutes

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General information

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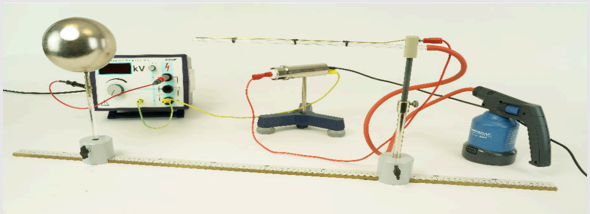
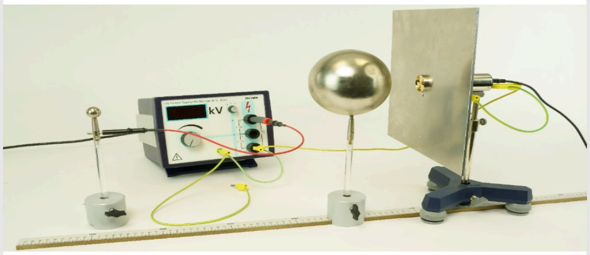
Application



measurement of potential



measurement of electric field

Electric fields are the cause of many phenomena, especially in particle physics.

The Coulomb potential and the electric field can be studied on a charged sphere. Outside the sphere, these radial fields behave analogously to the fields of point charges.

In this experiment, the fields are investigated as a function of the voltage applied to the sphere and the distance.

The electric field strength is determined using the principle of the mirror charge.

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Other information (1/2)

Prior knowledge

The basic principle of electric charges should be known. To describe the charged sphere its capacity must be known. Furthermore, the basic principle of fields and potential should already be known.

Scientific principle

Since the fields depend on the charge, but voltages are applied to the sphere, the sphere is regarded as a capacitor in order to be able to investigate the Coulomb potential and the electric field as a function of voltage and distance.

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Other information (2/2)

Learning objective

After completing this experiment, the potential of a charged sphere and the strength of its electric field can be theoretically calculated and experimentally determined, by using the principle of the mirror charge.

Tasks

- Determination of the Coulomb potential of the charged sphere as a function of voltage and distance.
- Determination of the electric field strength of the charged sphere as a function of voltage and distance.

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Safety instructions

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The general instructions for safe experimentation in science lessons apply to this experiment.

Working with high voltage is always dangerous and requires increased caution. Make sure that neither you nor others can accidentally touch parts connected to the high voltage source. For your safety and the safety of the equipment, make sure that the grounding is connected.

Corresponding to norm EN 61010-1 the output voltage of the PHYWE high voltage power supply unit (13673-93) can be regarded as non-hazardous because the direct current is lower than 2 mA.

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Theory (1/4)

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The potential outside the charged spherical shell corresponds to that of a point charge with:

$$\varphi = \frac{1}{4\pi\epsilon_0}\frac{Q}{r} \quad (1)$$

Where r is the distance to the center of the sphere and Q is the charge of the sphere.

Using the capacity C of the sphere with the radius R, the charge at voltage U is

$$Q = C \cdot U = 4\pi\epsilon_0 \cdot R \cdot U \quad (2)$$

By introducing (2) into (1) yields

$$\varphi = \frac{R}{r} \cdot U \quad (3)$$

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Theory (2/4)

To investigate the potential as a function of the distance, a double logarithmic representation of the measured values is suitable.

The logarithm of equation (3) leads to

$$\log\varphi = -\log r + \log R + \log U = -\log r + k \quad (4)$$

with a constant k at constant R and U.

Using (4) the measured values for the location-dependent measurements can be examined. With double logarithmic representation a straight line with the slope $m = -1$ results.

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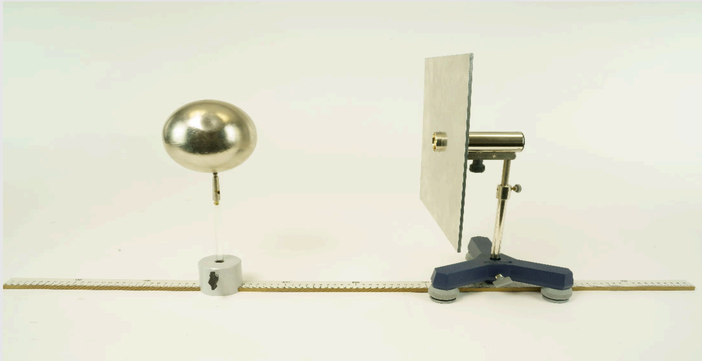
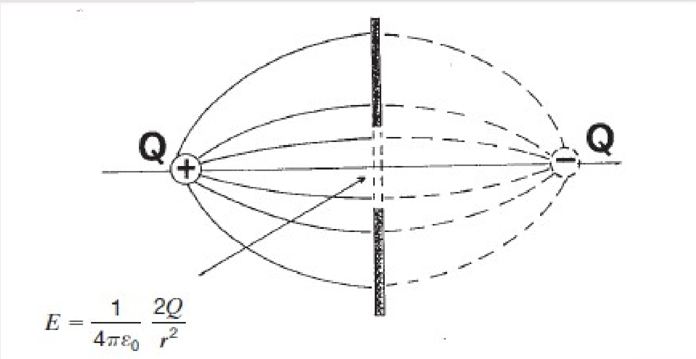
Theory (3/4)

To measure the field strength a capacitor plate is mounted on the electric field meter.

A virtual mirror charge is induced by this plate as shown in the figure to the right.





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Theory (4/4)

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If the potential field φ is known, the electric field E can be described as the negative gradient of the potential.

$$E = -\text{grad}\varphi = -\frac{d\varphi}{dr} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2} \tag{5}$$

Replacing the value of Q in (5) by (2) and considering the doubling of the charge, results in:

$$E = \frac{2R}{r^2} \cdot U \tag{6}$$

For the evaluation in double logarithmic representation, the electric field is calculated similar to (4):

$$\log E = -2 \cdot \log r + \log R + \log U = -2 \cdot \log r + k \tag{7}$$

resulting in a straight line with the slope $m = -2$.

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Equipment

Position	Material	Item No.	Quantity
1	Potential probe	11501-00	1
2	Capacitor plate w.hole	11500-05	1
3	PHYWE High voltage power supply with digital display, 10 kV DC: 0... ± 10 kV, 2 mA	13673-93	1
4	Conductor ball, d 20mm	06236-00	1
5	Conductor ball, d 40mm	06237-00	1
6	Conductor ball, d 120mm	06238-00	1
7	High-value resistor, 10 MOhm	07160-00	1
8	Insulating stem	06021-00	2
9	Barrel base expert	02004-00	2
10	Stand tube	02060-00	1
11	Tripod base PHYWE	02002-55	1
12	Meter scale, l = 1000 mm	03001-00	1
13	Rubber tubing, i.d. 6 mm	39282-00	1
14	Blow lamp, butan cartridge,X2000	46930-00	1
15	Butane cartridge C206, without valve, 190 g	47535-01	2
16	Connecting cord, 30 kV, 500 mm	07366-00	1
17	Connecting cord, 32 A, 750 mm, red	07362-01	1
18	Connecting cord, 32 A, 750 mm, green-yellow	07362-15	2
19	Connecting cord, 32 A, 250mm, green-yellow	07360-15	2
20	Electric Field Meter	11500-30	1

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Setup and procedure

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Setup (1/2)

- Mount the conducting sphere on the insulated stand and connect it with the high voltage cable via the $10 M\Omega$ safety resistor to the positive pole of the high voltage source.
- Connect the negative pole of the high voltage source and the backside of the electric field meter to ground.
- Place the protective cap on the electric field meter and connect it via USB to a computer.
- Start the program EFMXX5_ReadOut. Click on "Device info" and "Continue". Start zero adjustment and follow the instructions.
- Remove the cap and mount the voltage measuring attachment (golden cap) on the electric field meter.
- Plug the potential measuring probe to the red connection socket of the voltage measuring attachment.
- Connect the glass tube of the potential measuring probe with the rubber tubing to the burner.

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Setup (2/2)

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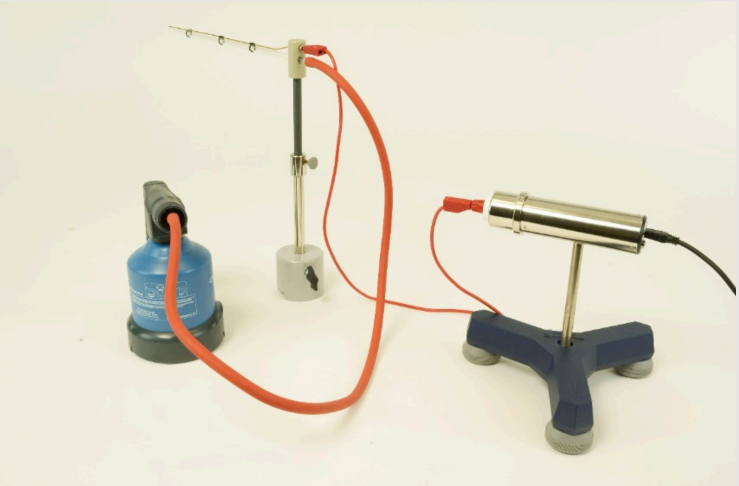

Electric field meter with voltage measurement attachment, potential probe and burner

- "Start measurement display" and choose "Measure mode" "Voltmeter MK 11".
- With the voltage measuring attachment the electric field meter is capable of measuring voltages in the ranges of $50\,V$, $250\,V$, $500\,V$ and $2500\,V$.
- Press "Start" for data aquisition.
- Adjust measurement range as needed.

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Procedure (1/5)

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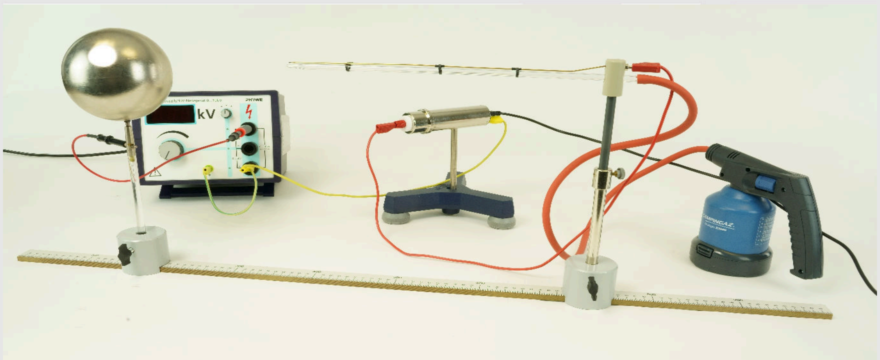
Measurement 1: Electrostatic potential of a charged sphere as a function of voltage

Place the measuring probe tip about $25\,cm$ from the center of the sphere. Light up the flame and adjust the gasflow of the burner, so that the flame is very stable and fully enwraps the probe's tip (~ 5mm above the tip).



- Apply voltages in steps of $0.5\,kV$ beginning from $1\,kV$ up to a maximum of $4\,kV$ to the sphere with diameter $2R = 12\,cm$.
- Note your measurements in table 1 of the evaluation section.

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Procedure (2/5)

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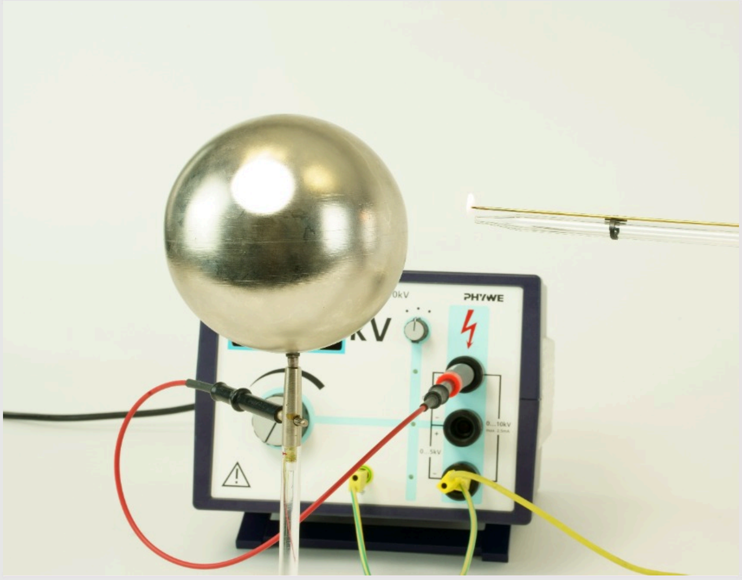

Measurement 2: electrostatic potential of a charged sphere as a function of distance

- Apply a voltage of $1\,kV$ to the sphere with diameter $2R = 12\,cm$.
- Take measurements for steps of $1\,cm$ up to $10\,cm$.
- Note your measurements in table 2 of the evaluation section.
- Repeat the measurement for the conducting sphere of $2R = 4\,cm$.

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Procedure (3/5)

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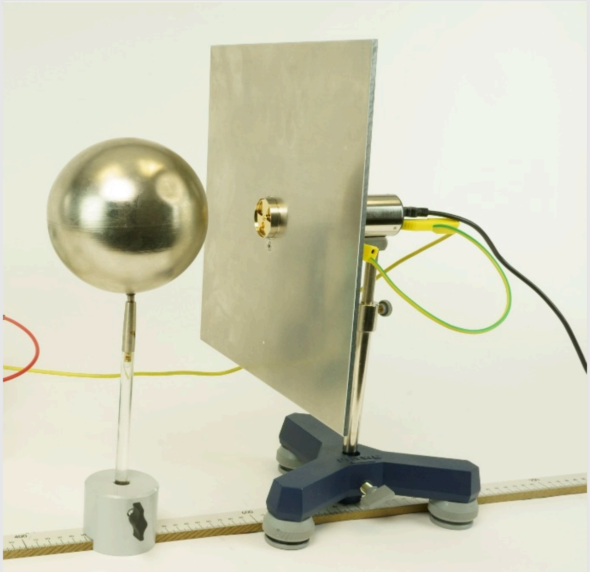

Setup for the measurement of the electric field:

- Replace the voltage measuring attachment at the electric field meter with the capacitor plate.
- Adjust the height of the electric field meter with attached capacitor plate in the holder, so that its central axis lies in the equator plane of the test sphere.
- Change "Measure mode" to "E-Fieldmeter"
- Press "Start" for data aquisition.
- Adjust measurement range as needed.

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Procedure (4/5)

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Measurement 3: Electric field strength of a charged sphere as a function of the charging voltage

- Place the sphere with diameter $2R = 12\,cm$ successively at distances of $r_1 = 25\,cm$, $r_2 = 50\,cm$ and $r_3 = 75\,cm$.
- Charge the sphere in steps of $1\,kV$ up to $10\,kV$ by applying the voltage to the small sphere on the insulating support and touching the test sphere with it. (Note: Do not directly charge the test sphere. Due to insulation issue this will lead to false experimental results)
- After charging set the voltage back to zero, switch off the voltage supply and touch the small sphere with the earthed cable. Note the resulting values in table 3 and discharge the sphere after every measurement by briefly touching it with the earthed cable.
- Repeat the measurement with the $2R = 4\,cm$ sphere at $r_4 = 25\,cm$

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Procedure (5/5)

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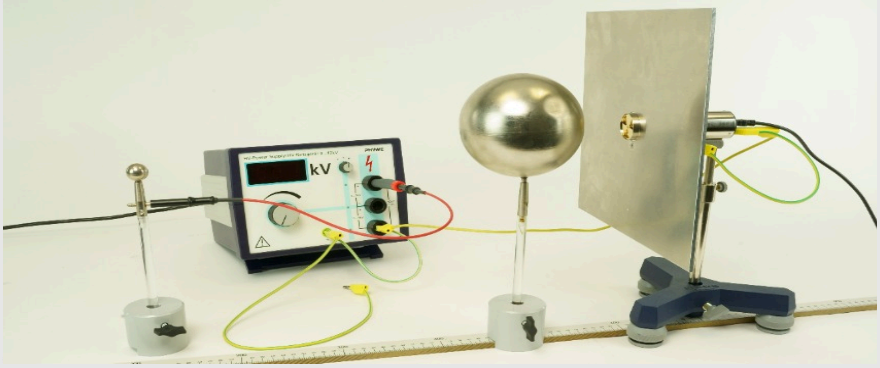
Measurement 4: Electric field strength of a charged sphere as a function of distance

Charge the sphere with diameter $2R = 12\,cm$ to $10\,kV$ via the small sphere as before. After charging set the voltage back to zero, switch off the power supply and touch the small sphere with the earthed cable.



- Measure the electric field in steps of $5\,cm$ beginning at $r = 15\,cm$ up to $r = 60\,cm$.
- Note the resulting values in table 4 and discharge the sphere at the end by briefly touching it with the earthed cable.

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Evaluation (1/4) Table 1

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Note the measured values for the Coulomb potential φ.

Create a graph from your measurement series.

$U\,[kV]$	1	1.5	2	2.5	3	3.5	4
$\varphi\,[V](r=25cm; R=6cm)$							

Create a graph from your measurement series, analogously to the example at $r = 18\,cm$:

Since $\varphi = \frac{R}{r} \cdot U$ the slope m of the linear regression $\varphi = m \cdot U$ should match with the quotient R/r.

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Evaluation (2/4) Table 2

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Note the results of your measurement of the Coulomb potential φ as a function of distance r.

Draw a graph of the measurement series with double logaritmic scale to check the slope.

$r\,[cm]$	7	8	9	10	11	12	13	14	15	16
$\varphi\,[V](R=6cm)$										

$r\,[cm]$	3	4	5	6	7	8	9	10	11	12
$\varphi\,[V](R=2cm)$										

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Evaluation (3/4) Table 3

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Note the measured values for the electric field strength E for the four series and plot the graphs.

$U\,[kV]$	1	2	3	4	5	6	7	8	9	10
$E\,[kV/m]$ (r=25cm; R=6cm)										
$E\,[kV/m]$ (r=50cm; R=6cm)										
$E\,[kV/m]$ (r=75cm; R=6cm)										
$E\,[kV/m]$ (r=25cm; R=2cm)										

Since $E = \frac{2R}{r^2} \cdot U$ the slope m of the linear regression $E = m \cdot U$ should match with the quotient $2R/r^2$.

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Evaluation (4/4) Table 4

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Note the results of your measurement of the electric field strength E as a function of distance r for the $R = 6cm$ sphere at voltage $V = 10kV$.

Plot the resulting graph with double logaritmic scale to check the slope.

$r\,[cm]$	15	20	25	30	35	40	45	50	55	60
$E\,[kV/m]$										

You can also simply plot the resulting electric field strengths with respect to the squared reciprocal distance $1/r^2\ [1/m^2]$ (note that the distances were measured in cm). Since $E = 2R \cdot U \cdot \frac{1}{r^2}$ the slope m of the linear regression $E = m \cdot \frac{1}{r^2}$ should then match with $2R \cdot U$.

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