

PROBLEM

Problem E1



Problem E1. The magnetic permeability of water (10 points)

Part A. Qualitative shape of the water surface (1 points)

Observing reflections from the water surface (in particular, those of straight lines, such as the edge of a sheet of paper), it is easy to see that the profile has one minimum and has a relatively flat bottom, ie. the correct answer is “Option D” (full marks are given also for Option B). This profile implies that water is pushed away from the magnet, which means $\mu < 1$ (recall that ferromagnets with $\mu > 1$ are pulled).

Part B. Exact shape of the water surface (7 points)

i. (1.6 pts) The height of the spot on the screen y is tabulated below as a function of the horizontal position x of the caliper. Note that the values of y in millimetres can be rounded to integers (this series of measurements aimed as high as possible precision).

| | | | | | | | | |
|--------|------|------|------|------|------|------|------|------|
| x (mm) | 10 | 15 | 20 | 25 | 30 | 32 | 34 | 36 |
| y (mm) | 11.5 | 15.6 | 19.8 | 24.3 | 30.2 | 33.2 | 37.2 | 40.5 |
| x (mm) | 38 | 40 | 42 | 44 | 46 | 48 | 50 | 52 |
| y (mm) | 42.2 | 41.4 | 40.3 | 40.3 | 40.8 | 42 | 43.2 | 44.4 |
| x (mm) | 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 |
| y (mm) | 45.3 | 45.8 | 45.4 | 44.4 | 43.6 | 46.2 | 50 | 53.6 |
| x (mm) | 70 | 72 | 74 | 76 | 78 | 80 | 85 | 90 |
| y (mm) | 56.7 | 59.5 | 61.6 | 63.5 | 65.3 | 67 | 70.9 | 74.9 |

ii. (0.7 pts)



On this graph, the data of two different water levels are depicted; blue curve corresponds to a water depth of *ca* 2 mm (data given in the table above); the violet one — to 1 mm.

iii. (0.5 pts) If the water surface were flat, the dependence of x on y would be linear, and the tangent of the angle α_0 would be given by $\tan \alpha_0 = \frac{\Delta y}{\Delta x}$, where Δx is a horizontal displacement of the pointer, and Δy — the respective displacement of the spot height. For the extreme positions of the pointer, the beam hits the water surface so far from the magnet that there, the surface

is essentially unperturbed; connecting the respective points on the graph, we obtain a line corresponding to a flat water surface — the red line. Using these two extreme data points we can also easily calculate the angle $\alpha_0 = \arctan \frac{74.9-11.5}{90-10} \approx 38^\circ$.

iv. (1.4 pts) For faster calculations, $y - y_0 - (x - x_0) \tan \alpha_0$ (appearing in the formula given) can be read from the previous graph as the distance between red and blue line; the red line is given by equation $y_r = y_0 + (x - x_0) \tan \alpha_0$. One can also precalculate $\frac{1}{2} \cos^2 \alpha_0 \approx 0.31$. The calculations lead to the following table (with $z = \tan \beta \cdot 10^5$; as mentioned above, during the competition, lesser precision with two significant numbers is sufficient).

| | | | | | | | | |
|--------|------|------|------|------|------|------|------|------|
| x (mm) | 10 | 15 | 20 | 25 | 30 | 32 | 34 | 36 |
| z | 0 | 10 | 27 | 66 | 204 | 303 | 473 | 591 |
| x (mm) | 38 | 40 | 42 | 44 | 46 | 48 | 50 | 52 |
| z | 597 | 428 | 239 | 128 | 53 | 26 | 0 | -26 |
| x (mm) | 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 |
| z | -72 | -145 | -278 | -449 | -606 | -536 | -388 | -254 |
| x (mm) | 70 | 72 | 74 | 76 | 78 | 80 | 85 | 90 |
| z | -154 | -74 | -40 | -20 | -6 | 2 | -2 | 0 |

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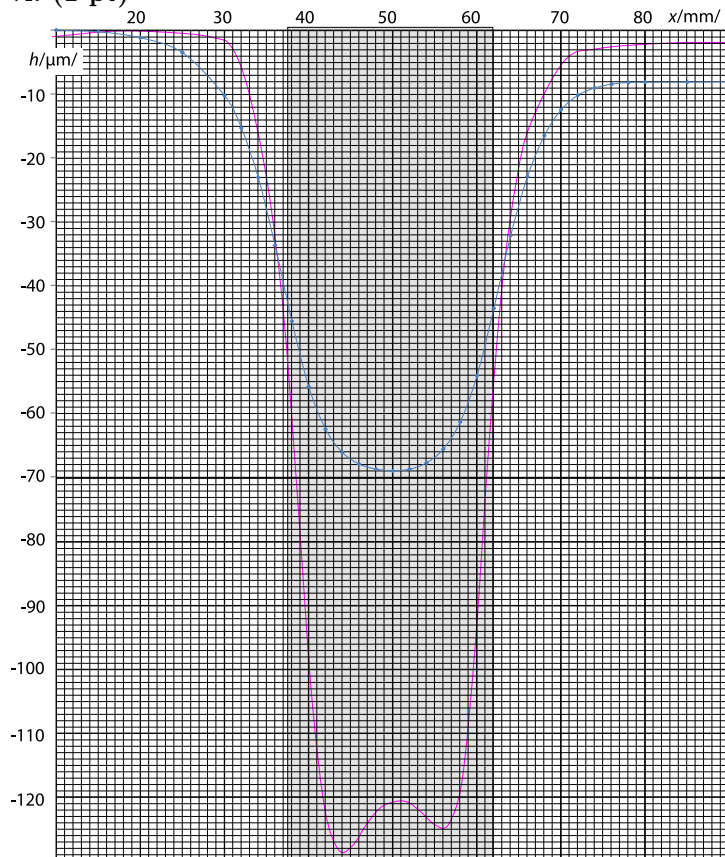
v. (1.6 pts) The water height can be obtained as the integral $h = \int \tan \beta dx$. Thus, we calculate the water height row-by-row, by adding to the height in the previous row the product of the horizontal displacement $x_{i+1} - x_i$ with the average slope $\frac{1}{2}(\tan \beta_{i+1} + \tan \beta_i)$.

| | | | | | | | | |
|------------------------|----|----|----|----|----|----|----|----|
| x (mm) | 10 | 15 | 20 | 25 | 30 | 32 | 34 | 36 |
| $-h$ (μm) | 0 | 0 | 1 | 4 | 10 | 15 | 23 | 34 |
| x (mm) | 38 | 40 | 42 | 44 | 46 | 48 | 50 | 52 |
| $-h$ (μm) | 46 | 56 | 63 | 66 | 68 | 69 | 69 | 69 |
| x (mm) | 54 | 56 | 58 | 60 | 62 | 64 | 66 | 68 |
| $-h$ (μm) | 68 | 66 | 61 | 54 | 44 | 32 | 23 | 17 |
| x (mm) | 70 | 72 | 74 | 76 | 78 | 80 | 85 | 90 |
| $-h$ (μm) | 12 | 10 | 9 | 8 | 8 | 8 | 8 | 8 |

Note that the water level height at the end of the table should be also 0 (this corresponds also to an unperturbed region); the non-zero result is explained by the measurement uncertainties. One can improve the result by subtracting from h a linear trend $8 \mu\text{m} \cdot \frac{x-10 \text{ mm}}{80 \text{ mm}}$.

If the water level above the magnet is 1 mm, the water level descends below its unperturbed level at the axis of the magnet by ca $120 \mu\text{m}$.

vi. (1 pt)



Similarly to the previous figure, blue curve corresponds to a water depth of ca 2 mm, (data given in the table above), and the violet one — to 1 mm.

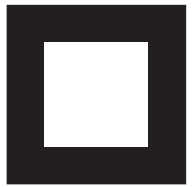
The position of the magnet can be found by measuring the caliper (find the positions when the laser beam hits the edges of the magnet and determine the distance between these positions — the result is ca 24 mm), and using the symmetry: magnet is placed symmetrically with respect to the surface elevation curve.

Part C. Magnetic permeability (2 points)

Water surface takes an equipotential shape; for a unit volume of water, the potential energy associated with the magnetic interaction is $\frac{B^2}{2\mu_0}(\mu^{-1}-1) \approx B^2 \frac{1-\mu}{2\mu_0}$; the potential energy associated with the Earth's gravity is ρgh . At the water surface, the sum of those two needs to be constant; for a point at unperturbed surface, this expression equals to zero, so $B^2 \frac{\mu-1}{2\mu_0} + \rho gh = 0$ and hence, $\mu - 1 = 2\mu_0 \rho gh / B^2$. Here, $h = 120 \mu\text{m}$ stands for the depth of the water surface at the axis of the magnet; note that we have compensated the cumulative error as described at the end of the previous task and obtained h as the difference between the depth at the magnet's axis ($121 \mu\text{m}$) and the half-depth at the right-hand-side of the graph ($1 \mu\text{m}$). Putting in the numbers, we obtain $\mu - 1 = -1.2 \times 10^{-5}$.

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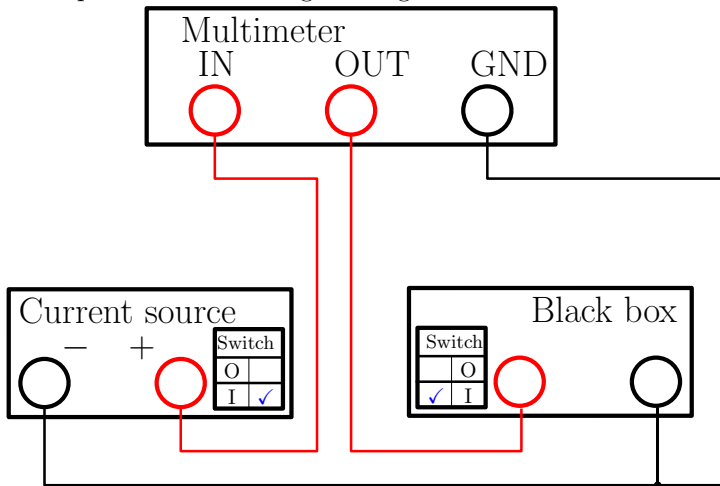
Problem E2



Problem E2. Nonlinear Black Box (10 points)

Part A. Circuit without inductance (7 points)

It is possible to make all the measurements needed for this problem with a single circuit as shown in the figure. While the current source is switched on, we are charging the capacitor in the black box, until the current $I(V_{\max})$ through the nonlinear element equals to the output current I_0 of the current source. $V_{\max} = 540 \pm 40$ mVs varies from one experimental setup to another. When the current source is switched off or disconnected, the capacitor will discharge through the nonlinear element.



i. (1 pt) During charging of the capacitor from $V = 0$ to $V = V_{\max}$ we note that the output of the current source is constant ($I_0 = 6.0$ mA) close to the precision of the multimeter.

ii. (1.2 pts) Using the definition of differential capacitance, we can calculate the current through the capacitor in the black box from the time derivative of the voltage on the black box.

$$I_c = \frac{dQ}{dt} = \frac{dQ}{dV} \frac{dV}{dt} = C(V) \dot{V}$$

There are several ways to determine the capacitance used in the black box based on chosen voltage.

- When the voltage on the black box is close to zero, the current through the nonlinear element is also close to zero, because $I(V = 0) = 0$. After switching the current source on, most of the input current I_0 will at first go through the capacitor.

$$C_0 = I_0 / \dot{V}_{\uparrow}(V = 0)$$

This can be measured more precisely after first reversing the polarity of the current source and charging the capacitor backwards, because the multimeter does not display derivatives when they change sharply (as in few moments after switching the current source on).

Example measurements taken this way follow.

| | | | |
|--------------------------------|------|------|------|
| $\dot{V}_{\uparrow}(0)$ (mV/s) | 3.51 | 3.32 | 3.55 |
| C_0 (F) | 1.71 | 1.81 | 1.69 |

$$C_0 = 1.74 \text{ F}$$

- When the voltage on the black box is V_{\max} , the current through the nonlinear element is I_0 . Switching the current source off, we will have the capacitor discharging with the same current.

$$C_0 = -I_0 / \dot{V}_{\downarrow}(V = V_{\max})$$

- We can also measure the capacitance for any intermediate voltage as in **A-iv**.

iii. (2.2 pts) If we neglect the nonlinearity of the capacitor, there are (at least) two ways to obtain the current–voltage characteristic of the nonlinear element in the black box.

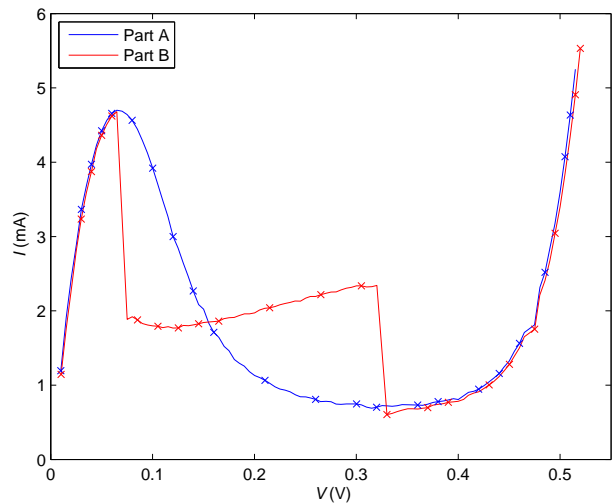
- Applying Kirchhoff's I law to the charging capacitor,

$$I(V) = I_c - C_0 \dot{V}_{\uparrow}(V).$$

An $I(V)$ characteristic obtained by charging the capacitor is shown on the following figure.

- Applying Kirchhoff I law to the discharging capacitor,

$$I(V) = -C_0 \dot{V}_{\downarrow}(V).$$



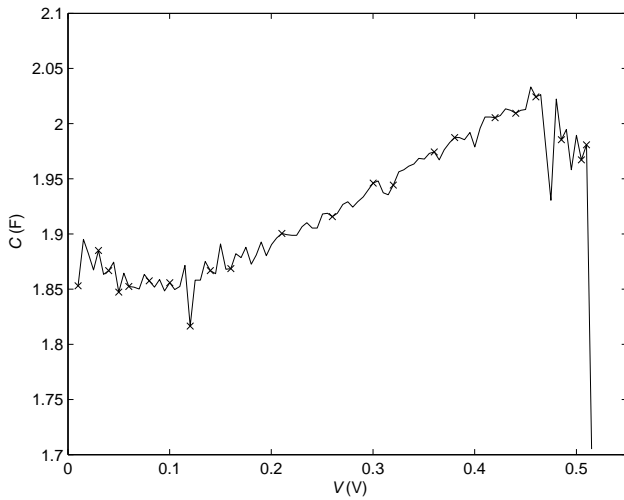
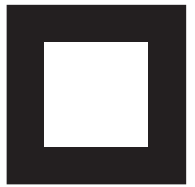
iv. (2.6 pts) In order to obtain the differential capacitance, we solve a system of linear equations by eliminating $I(V)$:

$$\begin{cases} I_0 = \dot{V}_{\uparrow} C(V) + I(V) \\ I(V) = -\dot{V}_{\downarrow} C(V); \end{cases} \implies C(V) = \frac{I_0}{\dot{V}_{\uparrow} - \dot{V}_{\downarrow}}.$$

Therefore we need to take measurements during both charging and discharging the capacitor in the black box at the same voltages. A graph of measurement results follows.

PROBLEM

Problem E2



Part B. Circuit with inductance (3 points)

Measuring and plotting the current–voltage characteristic of the nonlinear element in the same way as in part **A-iii**, we obtain a graph that differs only in the negative differential resistance ($I'(V) < 0$) region, in our case $70 \text{ mV} < V < 330 \text{ mV}$. This is the region where, when we look at small-signal oscillations, the nonlinear element behaves as a negative-valued Ohmic resistance. After enabling the inductance we have a LC circuit whose oscillations are amplified (instead of being dampened) by the negative differential resistance. Because the resonant frequency $\omega = \sqrt{\frac{1}{LC_p}} \sim 30 \text{ MHz}$ (with C_p being the capacitance of the nonlinear element) is high, we actually measure the average current through the nonlinear element, while the real current oscillates all over the region of negative differential resistance.

The 43rd International Physics Olympiad — July 2012

Grading scheme: Experiment

General rules This grading scheme describes the number of points allotted for the design of the experiments, measurements, plotting, and formulae used for calculations. In the case of a formula, points are allotted for each term entering it. If a certain term of a useful formula is written incorrectly, 0.1 is subtracted for a minor mistake (eg. missing non-dimensional factor); no mark is given if the mistake is major (with non-matching dimensionality). Points for the data measurements and calculations are not given automatically: the data which are clearly wrong are not credited.

If the numerical data miss units, but the units can be

guessed, 25% of points will be subtracted for the corresponding line in this grading scheme (rounded to one decimal place). The same rule applies if there is a typo with units with a missing or redundant prefactor (milli-, micro-, etc); no mark is given if the mistake is dimensional (e.g Ampere instead of Volt).

No penalty is applied in these cases when a mistake is clearly just a rewriting typo (i.e. when there is no mistake in the draft).

No penalty is applied for propagating errors unless the calculations are significantly simplified (in which case mathematical calculations are credited partially, according to the degree of simplification, with marking granularity of 0.1 pts).

PROBLEM

Problem E1



Problem E1. The magnetic permeability of water (10 points)

Part A. Qualitative shape of the water surface (1 points)

Correct choice (B or D) — 0.5 pts;

Correct sign ($\mu < 1$) — 0.5 pts;

Part B. Exact shape of the water surface (7 points)

i. (1.6 pts) Data

Sufficient number of reasonably accurate ± 2 mm

data points: $(n - 9)/10$ pts but ≥ 0 and ≤ 0.9 — ≤ 0.9 pts;

(-0.1 if there is a sign error throughout the whole measurements)

Sufficient range of horizontal displacements: $(x - 45 \text{ mm})/50$

rounded to one decimal but ≥ 0 and ≤ 0.7 — ≤ 0.7 pts.

ii. (0.7 pts) Graph

Axes supplied with units — 0.1 pts;

Data points correctly plotted — 0.4 pts;

(each clearly wrong point on graph: -0.1 pt down to total 0)

More densely spaced data points

in the regions of fast change — 0.2 pts.

iii. (0.7 pts) Angle ($\approx 38^\circ$)

Idea: using the flat regions

far from the magnet — 0.5 pts

if the central part of the magnet is used: 0.1

Correct value: $\pm 5^\circ / \pm 10^\circ / > 10^\circ$ — 0.2/0.1/0 pts;

iv. (1.4 pts) Calculated table

According to the number of correctly calculated data points: (no marks if not obtained from the experimental data)

$0.1n$ up to $n = 10$;

correct sign — 0.1 pts

$1 + 0.05(n - 10)$ rounded down one decimal place for $n > 10$ (but ≤ 1.4);

v. (1.6 pts) Height profile

Idea of calculation: integration of surface slope — 0.7 pts
(if not stated but used correctly: full marks)

Δx multiplied by mean slope at that interval — 0.3 pts

For n correctly calculated data points: — $n/30$ pts
(but no more than 0.6; rounded down to one decimal place).

vi. (1 pt) Graph

Units on axes — 0.1 pts

Data points correctly plotted — 0.4 pts

(each clearly wrong point on graph: -0.1 pt down to total 0)

Correct qualitative shape: height difference

in wings less than the 20% of maximum variation) — 0.1 pts

flat central region: the water level height variation in the region spanning ± 10 mm around the magnet's axis

is less than $20 \mu\text{m}$) — 0.2 pts

Magnet indicated correctly: (width $24 \text{ mm} \pm 2 \text{ mm}$) — 0.1 pts

symmetrically positioned — 0.1 pts

Part C. Magnetic permeability (2 points)

Concept of equipotentiality — 0.8 pts

Formula correctly includes magnetic energy — 0.4 pts

Formula correctly includes gravitational energy — 0.2 pts

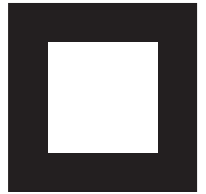
height at the middle corrected for the integration error — 0.2 pts

Value calculated correctly from the existing data — 0.1 pts

Value: magnitude correct within 50% — 0.2 pts

PROBLEM

Problem E2



Problem E2. Nonlinear Black Box (10 points)

Part A. Circuit without inductance (7 points)

Typical $I(V)$ and $C(V)$ curves can be found in solutions file and sample filled-in answer sheets. Because $I(V)$ and $C(V)$ curves shape, typical capacitance, I_0 and V_{\max} varies a bit from one setup to another, reference curves for particular setup can be acquired for grading when deemed necessary.

For questions i to iii, if the position of the switches on the circuit diagram is not indicated or marked incorrectly, take -0.1 pts from the marks for the circuit.

i. (1 pt)

Correct circuit — 0.3 pts

Measurements that cover 0 V to 480 mV — 0.3 pts

Correct value I_{\min} (± 0.4 mA) — 0.2 pts

Correct value I_{\max} (-0.4 mA/ $+0.8$ mA) — 0.2 pts

(unless only one data point)

In case of (single) measurement without the black box:

Circuit diagram — 0.1 pts

Measurement with the correct result — 0.1 pts

If only I_{\min} , I_{\max} together with a correct scheme documented, 0.7 pts in total; if only I_{\min} , I_{\max} , 0 pts in total.

ii. (1.2 pts) Measuring C_0 at $V = 0$

Correct circuit — 0.2 pts

(-0.1 for measuring voltage on ammeter + black box)

(-0.1 for wrong polarity of the black box)

Realising that $I_c = C_0 \dot{V}$ — 0.2 pts

Using the fact that $I_c = I_0$ when $V = 0$ — 0.2 pts

Correct result — 0.2 pts

-0.1 for error between $\pm 30\%$ and $\pm 50\%$

linear extrapolation to obtain \dot{V} at $V = 0$ — 0.4 pts

Alternatively instead of the last line

Three or more measurements — 0.2 pts

Precharging the capacitor to a negative voltage — 0.2 pts

Alternate solution C_0 at V_{\max}

Correct circuit — 0.2 pts

(-0.1 for measuring voltage on ammeter + black box)

Realising that $I_c = C_0 \dot{V}$ — 0.2 pts

Using the fact that $I_c = -I_0$ when $V = V_{\max}$ — 0.2 pts

Correct result — 0.1 pts

linear extrapolation to obtain \dot{V} at $V = V_{\max}$ — 0.2 pts

Three or more measurements — 0.2 pts

iii. (2.2 pts) For method:

If charging the capacitor:

Correct circuit — 0.2 pts

(-0.1 for measuring voltage on ammeter + black box)

(-0.1 for wrong polarity of the black box)

Realising that $I(V) = I_0 - C_0 \dot{V}_{\uparrow}$ — 0.2 pts

If discharging the capacitor:

Correct circuit (there are several) — 0.2 pts

(-0.1 for wrong polarity of the black box)

Realising that $I(V) = -C_0 \dot{V}_{\downarrow}$ — 0.2 pts

For measurements:

Total # of data correct data points (**V and \dot{V}**)

$10 \leq n < 15$; $15 \leq n < 20$; $n \geq 20$ — 0.1/0.2/0.3 pts

Additionally for correct data points (**when correct $I(V)$ is obtained**):

In range 0mV - 80mV at least 4/5 data pts — 0.1/0.2 pts

In range 80mV - 200mV at least 4/5 data pts — 0.1/0.2 pts

In range 200mV - 400mV at least 3 data pts — 0.1 pts

In range 400mV - 550mV at least 4/5 data pts — 0.1/0.2 pts

For plotting:

Units on axes — 0.1 pts

Data points correctly plotted — 0.4 pts

(each clearly wrong point on graph: -0.1 pts down to total 0)

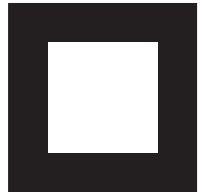
(0 pts for data points when data is based on physically incorrect assumptions)

Correct qualitative shape — 0.3 pts

(single maximum, single minimum with flat bottom, followed by fast rise)

PROBLEM

Problem E2



iv. (2.6 pts)

Correct circuit — 0.2 pts

(-0.1 for measuring voltage on ammeter + black box)

(-0.1 for wrong polarity of the black box)

(When the same circuit as for the question iii is given, and there are no correct measurements, 0 pts)

Idea to use the reverse cycle to pt iii— 0.4 pts

Writing the lin. eq for finding $C(V)$ — 0.4 pts

(No pts if only one Eq.)

Expressing from there $C(V)$ — 0.1 pts

Idea to use the same voltages for both cycles— 0.4 pts

(0.3 pts if intermediate values read from graph)

For plotting:

Units on axes — 0.1 pts

Data points correctly plotted — 0.4 pts

(each clearly wrong point on graph: -0.1 pt down to total 0)

(0 pts for data points when data is based on physically incorrect assumptions)

For correct data points **(when correct $C(V)$ is obtained)**:

In range 0mV - 80mV at least 4 data pts — 0.1 pts

In range 80mV - 200mV at least 4 data pts — 0.1 pts

In range 200mV - 400mV at least 3 data pts — 0.1 pts

In range 400mV - 550mV at least 4 data pts — 0.1 pts

For finding C_{\max} and C_{\min} :

Finding reasonable C_{\max} — 0.1 pts

Finding reasonable C_{\min} — 0.1 pts

Part B. Circuit with inductance (3 points)

For correct data points **(when correct $I(V)$ is obtained)**:

In range 0mV - 80mV at least 4 data pts — 0.1 pts

In range 80mV - 200mV at least 4 data pts — 0.1 pts

In range 200mV - 400mV at least 3 data pts — 0.1 pts

In range 400mV - 550mV at least 4 data pts — 0.1 pts

For plotting:

Units on axes — 0.1 pts

Data points correctly plotted — 0.4 pts

(each clearly wrong point on graph: -0.1 pt down to total 0)

(0 pts for data points when data is based on physically incorrect assumptions)

Correct qualitative shape — 0.3 pts

(two sharp falls, plateau in between)

For detecting differences:

Correct range for V :— 0.2 pts

Correct cond. for $I(V)$ — 0.5 pts

Noting that we have now LC -circuit— 0.2 pts

Noting that neg. resist. \rightarrow instability— 0.4 pts

(or something equivalent)

Mentioning emergence of oscillations— 0.2 pts

Noting that $I(V)$ is the average current— 0.3 pts