Experiment 1: Static response of a magnetically active fluid
Sample Solutions

General Note: these solutions look brief for many parts. Students do, however, have to manipulate the equipment and try to take good data, which will require taking some time. The solutions try to indicate some of the tricks.
Note that quantitative values will depend on the amount of fluid used and the containers – these should be tested and recalibrated when the experiment is used.

A1: Measurement taken on sample bottle: $\Delta z = 0.061 \pm 0.004$ m, when well balanced. (0.5 for good z, 0.3 for reasonable uncertainty) *Expect to see multiple attempts for full credit*

A2: Density difference gives the nett buoyant force, so balancing gravitational and magnetic forces: $\Delta\rho g = 3\,\chi B_r^2 a^4 l^2/8\mu_0 z^7$ (0.3)

Need to divide by g to rho, then substituting in the values for the large magnet yields

$\Delta\rho = 15$ kg m^{-3} (0.3)

Uncertainty sources: primarily z - hard to measure but can be controlled, and χ - not actually constant for a superparamagnet.
Any reasonable uncertainty method is fine. Using the data above, an estimate of 6 kg m^{-3} (0.2) could be made. Students should have some indication of where their labels come from.

Fresh bottles will be measured.

B1: $z_{crit} = 22 \pm 1$ mm (from uncertainty in when spikes appear) (0.2 + 0.1)

$\lambda = 6 \pm 1$ mm (from angle through the glass causing uncertainty about measurements of the incipient wavelength) (0.2 + 0.1)

Expect multiple attempts for full credit

Points will be given to good values. Doing this part is easiest if the bottle is on its side, although it can be done with the bottle upright.

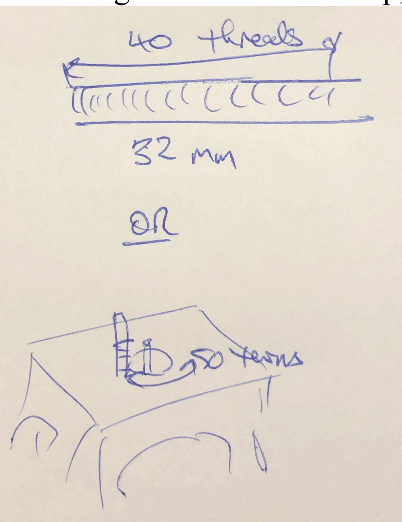
Note for future use: Values should be retaken using the actual experimental setup. They are sensitive to the bottles and magnets used.

B2: It may look as though there are a lot of points for nothing much here, but the credit is for the experimental skill that goes into taking high quality data. It is possible to be quite precise if one is careful and this will be rewarded here as well as the calculation details..

Surface tension may be calculated using the relationship above. It also requires the density difference from the earlier part, meaning that a large uncertainty in both parts will compound to the point where the uncertainty in this part is unreasonable.

For the values in these sample solutions $\sigma = 1.3 \times 10^{-2}$, N m^{-1} (0.3 if correct within an order of magnitude). Uncertainty estimate: in these data, $\Delta\sigma = 6 \times 10^{-3}$ N m^{-1} . (0.2 if correctly calculated from a reasonable method, 0.1 additional if less than 50%).

C1: There are many solution approaches.. All need to count threads and measure distance. For a diagram of a useful setup, **0.2**. For example:



0.2 for measurements and calculations.

Students should find that
$\Delta z = 0.80 \pm 0.02$ mm (**0.2**)

If a visual counting technique is used, at least three measurements are expected. If a turn-by-turn method, then distance measurements should be taken for at least three numbers of turns.

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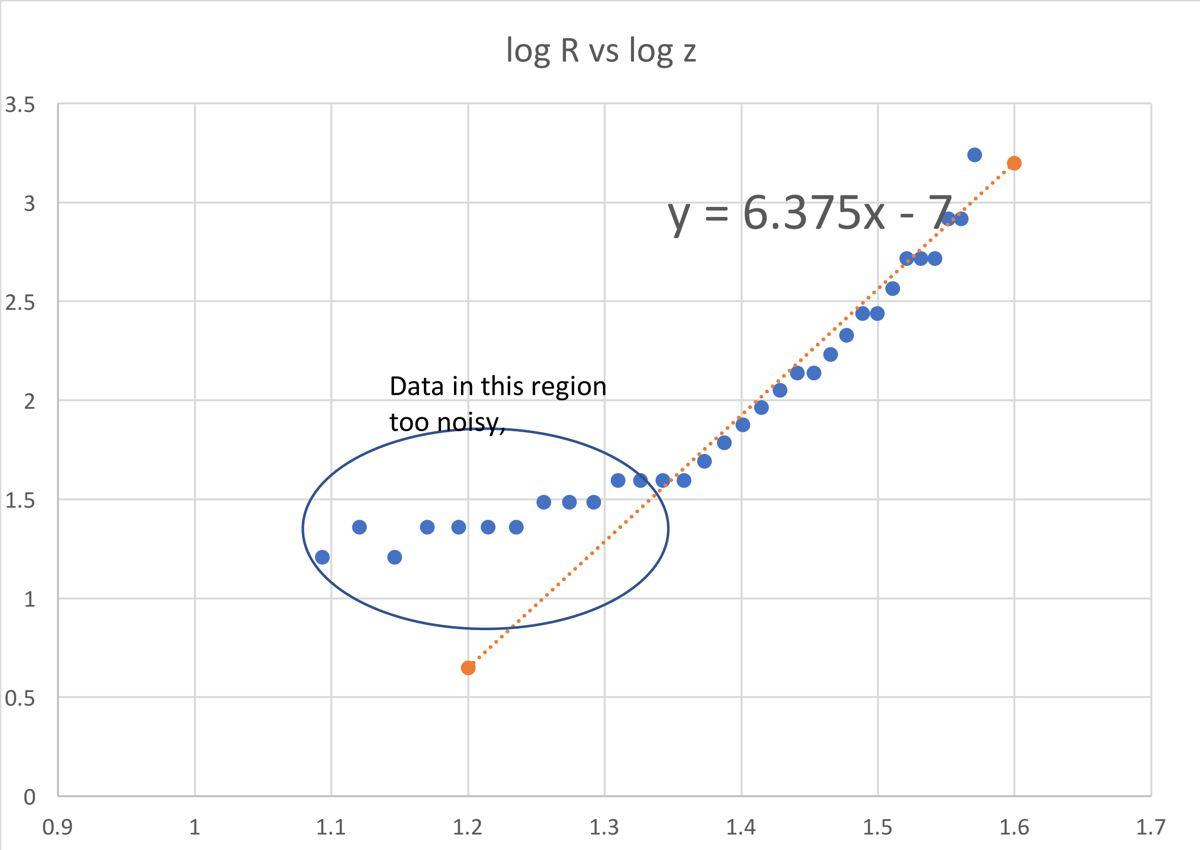
C2: Table of measurements:

turns	length of ligh	z (has offset)	M	R	z (corrected)	log z	log R
32.50	20.00	26.00	1.00	#DIV/0!	38.00	1.58	#DIV/0!
31.50	19.00	25.20	0.95	1748.00	37.20	1.57	3.24
30.50	18.00	24.40	0.90	828.00	36.40	1.56	2.92
29.50	18.00	23.60	0.90	828.00	35.60	1.55	2.92
28.50	17.00	22.80	0.85	521.33	34.80	1.54	2.72
27.50	17.00	22.00	0.85	521.33	34.00	1.53	2.72
26.50	17.00	21.20	0.85	521.33	33.20	1.52	2.72
25.50	16.00	20.40	0.80	368.00	32.40	1.51	2.57
24.50	15.00	19.60	0.75	276.00	31.60	1.50	2.44
23.50	15.00	18.80	0.75	276.00	30.80	1.49	2.44
22.50	14.00	18.00	0.70	214.67	30.00	1.48	2.33
21.50	13.00	17.20	0.65	170.86	29.20	1.47	2.23
20.50	12.00	16.40	0.60	138.00	28.40	1.45	2.14
19.50	12.00	15.60	0.60	138.00	27.60	1.44	2.14
18.50	11.00	14.80	0.55	112.44	26.80	1.43	2.05
17.50	10.00	14.00	0.50	92.00	26.00	1.41	1.96
16.50	9.00	13.20	0.45	75.27	25.20	1.40	1.88
15.50	8.00	12.40	0.40	61.33	24.40	1.39	1.79
14.50	7.00	11.60	0.35	49.54	23.60	1.37	1.69
13.50	6.00	10.80	0.30	39.43	22.80	1.36	1.60
12.50	6.00	10.00	0.30	39.43	22.00	1.34	1.60
11.50	6.00	9.20	0.30	39.43	21.20	1.33	1.60
10.50	6.00	8.40	0.30	39.43	20.40	1.31	1.60
9.50	5.00	7.60	0.25	30.67	19.60	1.29	1.49
8.50	5.00	6.80	0.25	30.67	18.80	1.27	1.49
7.50	5.00	6.00	0.25	30.67	18.00	1.26	1.49
6.50	4.00	5.20	0.20	23.00	17.20	1.24	1.36
5.50	4.00	4.40	0.20	23.00	16.40	1.21	1.36
4.50	4.00	3.60	0.20	23.00	15.60	1.19	1.36
3.50	4.00	2.80	0.20	23.00	14.80	1.17	1.36
2.50	3.00	2.00	0.15	16.24	14.00	1.15	1.21
1.50	4.00	1.20	0.20	23.00	13.20	1.12	1.36
0.50	3.00	0.40	0.15	16.24	12.40	1.09	1.21

1.0 points for the raw measurements of number of turns and M.
0.5 points for correct conversion to R.

Graph: **1.0** points for a graph allowing the calculation of the exponent.



0.5 for fit to correct region
0.5 for answer n within range 6 to 7 with reasonably estimated uncertainty.

Note: if students do not account for the distance between the surface of the stand and the surface of the fluid, the log-log graph will not have a proper linear region as it does not follow a reasonable power law. In this case there will be no credit for the conversion, the fit or the answer.

D1: Surface tension $\sigma \cong 2.3 \times 10^{-2}$N m^{-1}. **0.5** if within 10%, 0.3 within 20%, else 0.

D2: Table of sample measurements:

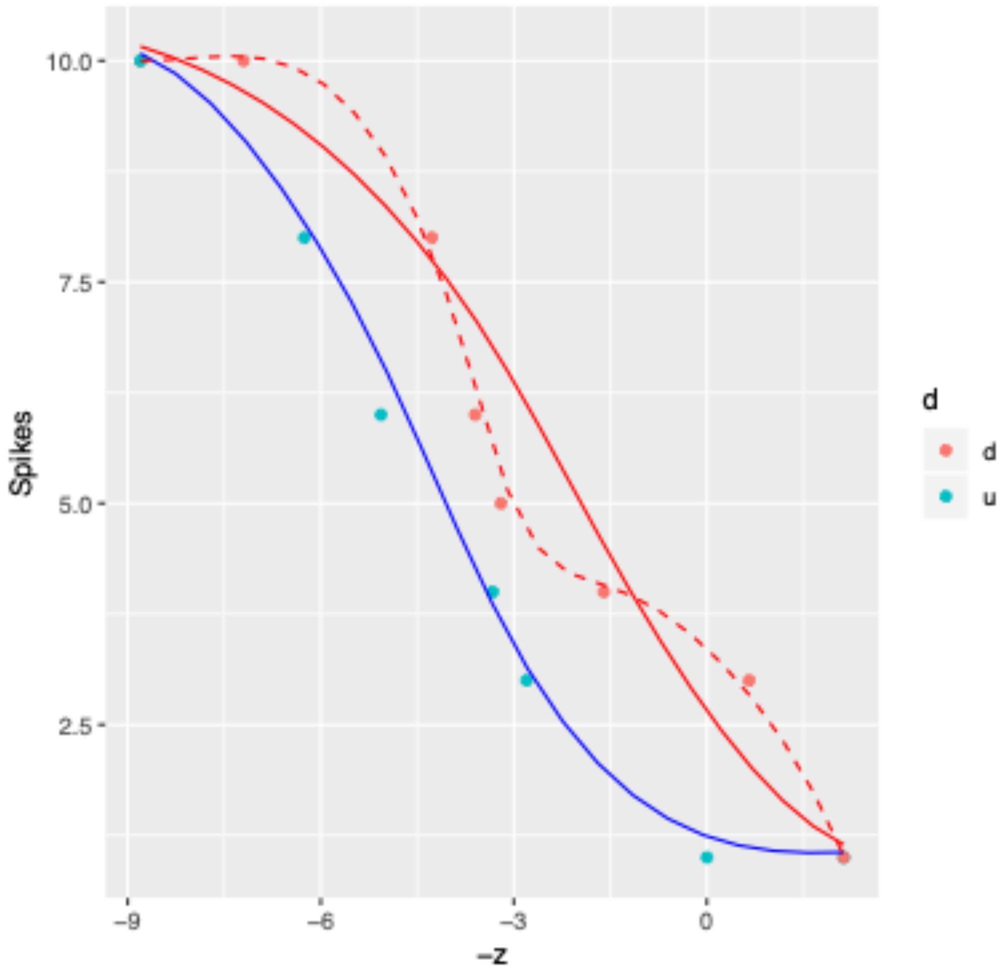
Spikes	Turns	z
1	0	0
3	3.5	2.8
4	4.16	3.328
6	6.33	5.064
8	7.82	6.256
10	11	8.8
10	2	7.2
8	5.66	4.272
6	6.5	3.6
5	7	3.2
4	9	1.6
3	11.82	-0.656
1	13.66	-2.128

In this data table, z has been measured to increase closer to the fluid; the question defines z to be the distance from the fluid. Students should either show explicitly how their variables are defined or transform to z as in the question. Either way, the graph in D3 must be in the appropriate direction and hence z transformed as necessary to match the question. In these solutions simply inverting z is used as the offset has no bearing on the hysteresis.

1.0 for at least 6 measurements each way, with conversion to z and a reasonable uncertainty estimate.

Note: this requires time and care to get the points of appearance and disappearance correctly. Missing values, or inaccurate jumps in spike number are indicative of sloppy work. Failing to use the calibrated screw thread (and instead using a ruler) renders the results significantly less accurate.

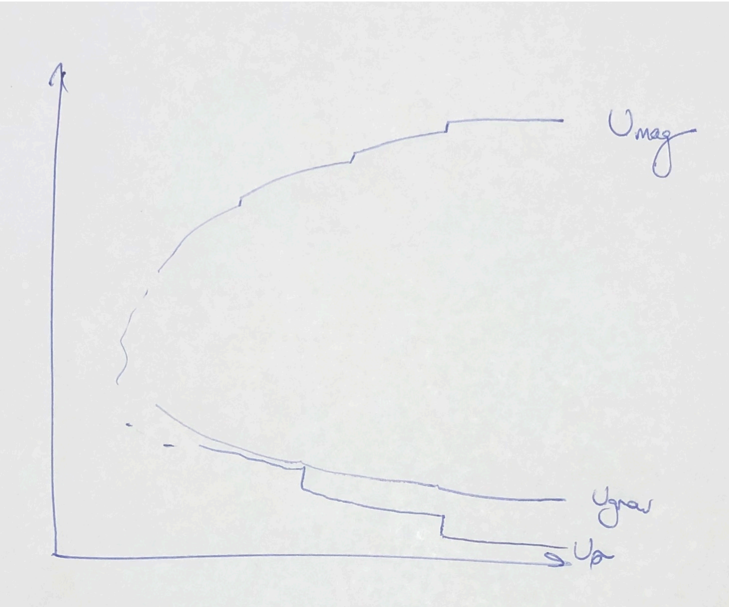
D3:



0.3 for a correctly plotted graph. 0.2 for each smooth curve fitting points. 0.3 if clear hysteresis shown: at least 1.5 mm separation in z between the up and down measurements.

Although the data are quantised they should still follow a reasonable curve. The curves shown above are blue for moving closer to the fluid, and red for moving away. The dashed curve is a likely result of a student joining points on the downward run – there is a waist in the data. The solid red curve is a typical averaging curve as seen at the APhO.

D4:



Key features:
Magnetic energy should decrease at a rapid rate as the magnet moves closer, following a power law – as long as it looks reasonable credit should be given without trying to determine the power. There should be small steps at the spike formations as there is a slight release of magnetic potential energy from the drawing of fluid along a new unstable surface.

Surface energy should jump at spike formation points and change much more slowly, although still steadily, throughout the rest of the time.

It is important that the overall energy decrease. Students should be able to tell this as the ferrofluid chamber will attract a magnet from underneath – most of the magnetic potential energy goes into lifting the magnet rather than being bound in the internal structure of the ferrofluid.

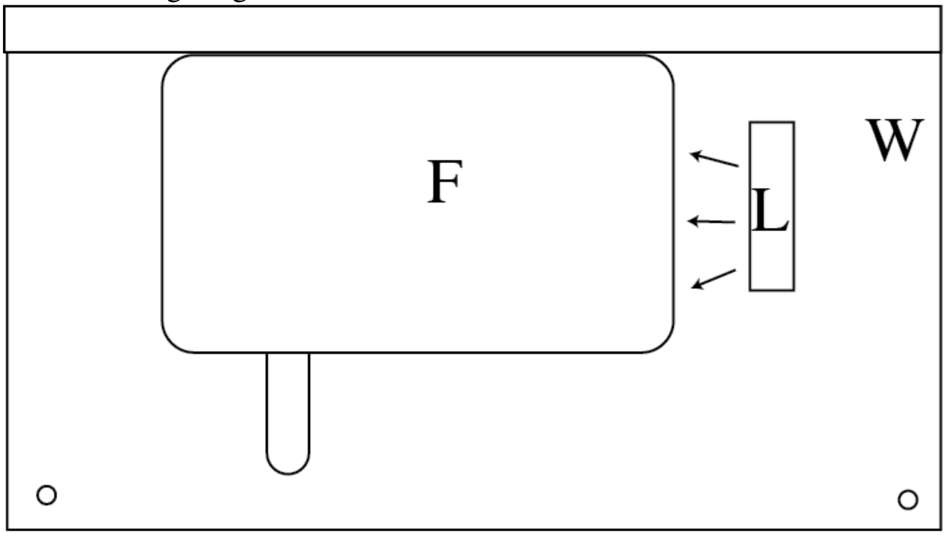
0.2 for each graph and 0.2 for correct behaviour of total energy.

Experiment
Q2 Wave pulses in a magnetically active fluid
Solutions

These quantitative values obtained depend strongly on the depth and other properties of the fluid, including how much oil has evaporated. The values mentioned in here correspond to the fluid as used at the APhO in Adelaide in May 2019.
Qualitative aspects of the solutions apply, even where values vary.

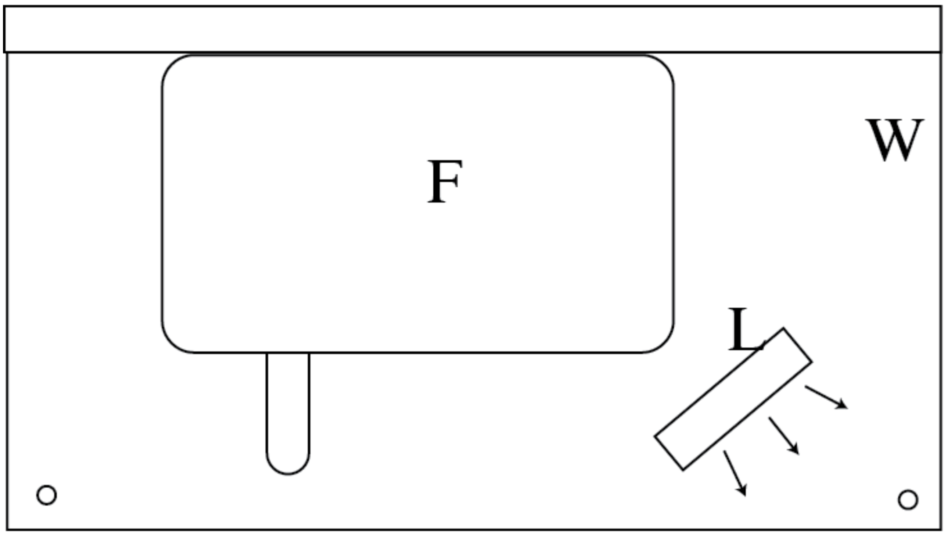
Throughout the light is used in two modes when taking videos. For parts A and D, the light is set up so that it is illuminating the ferrofluid surface through the sides of the box.

This direct lighting is used in Part A and Part F.



F – box with fluid
L – light
W – wooden base

Diffuse lighting is used for other parts. In this case the light is direction up and away from the box with ferrofluid.



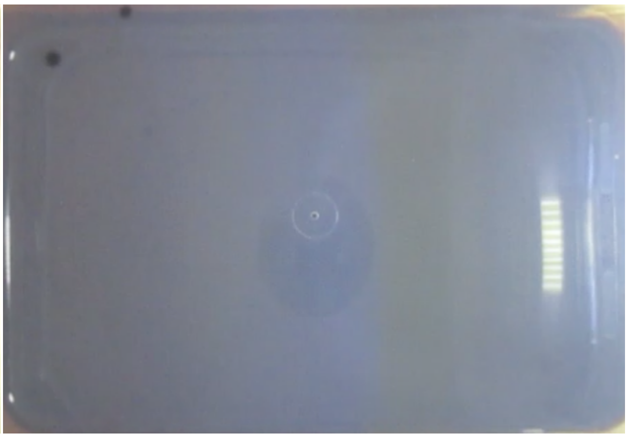
Part A Plane pulses

A.1 Direct lighting was used, so see above for diagram.

A.2 Some example frames from videos are shown below.

Note that the scale on the graticule does not directly measure position.

A measurement with a ruler of the internal length of the container is 17.3 ± 0.3 cm.
The distance is equivalent to 13.4 graticule squares, so there is a factor of 17.0/13.4 to convert from graticule squares to cm.

The images above show two frames from a video of a plane pulse. The videos are recorded at 25 fps by default

Frames	Distance (graticule squares)	Distance (m)	Speed (m/s)
8	6.5	0.83	0.26
7	6.0	0.76	0.27
9	6.8	0.85	0.24

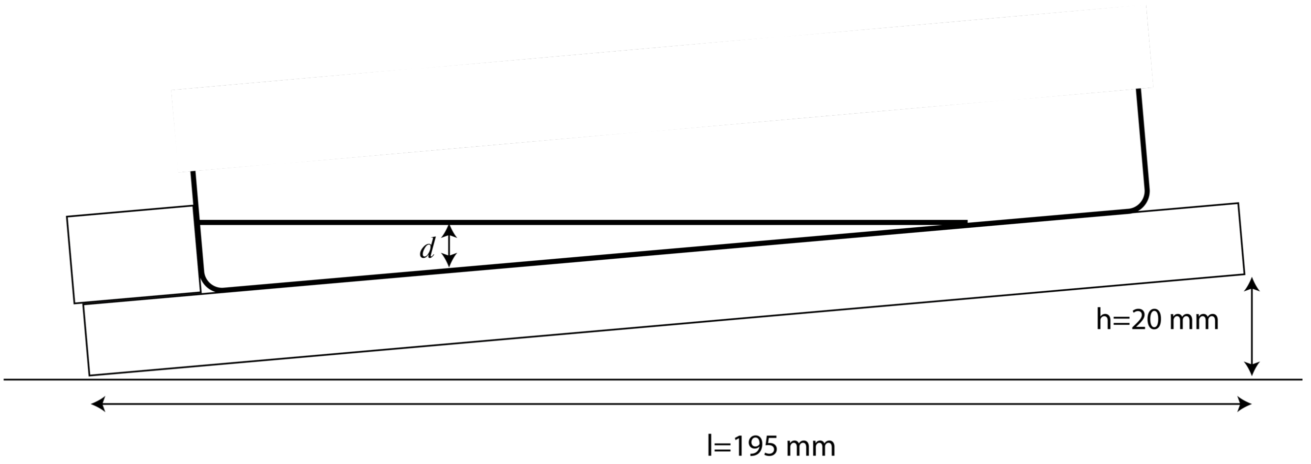
This gives $v = 0.26 \pm 0.02$ m/s

A.3 The uncertainty is estimated from the spread of values.

Part B Wave pulses in fluid of varying depth

B.1

i.



$h = 20 \pm 1$ mm, $l = 195 \pm 2$ mm. The latter uncertainty is larger due to difficulty lining up ruler with projection of end of the board.

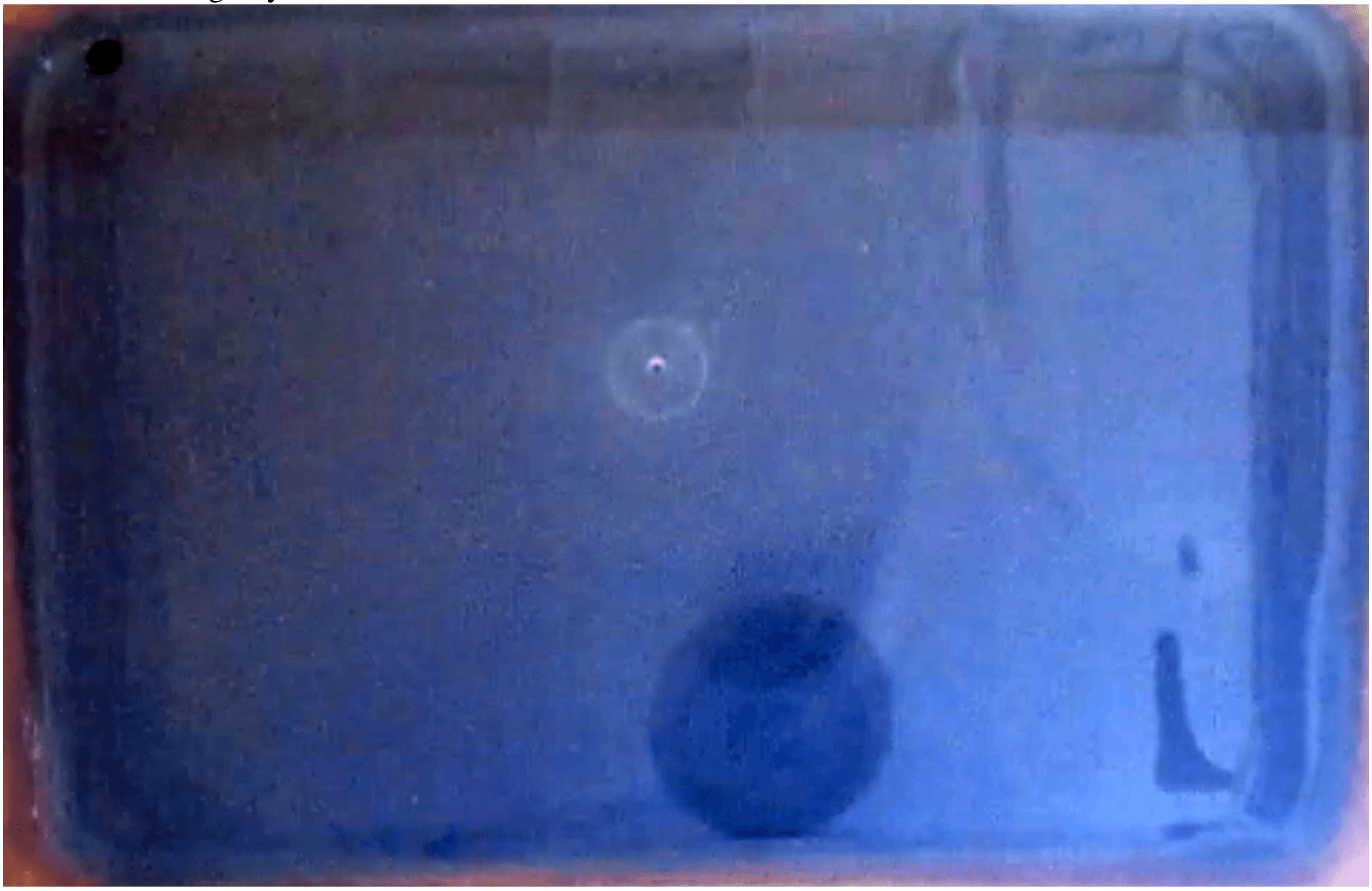
ii.

Since the depth varies linearly, $d = y\ tan\theta$.

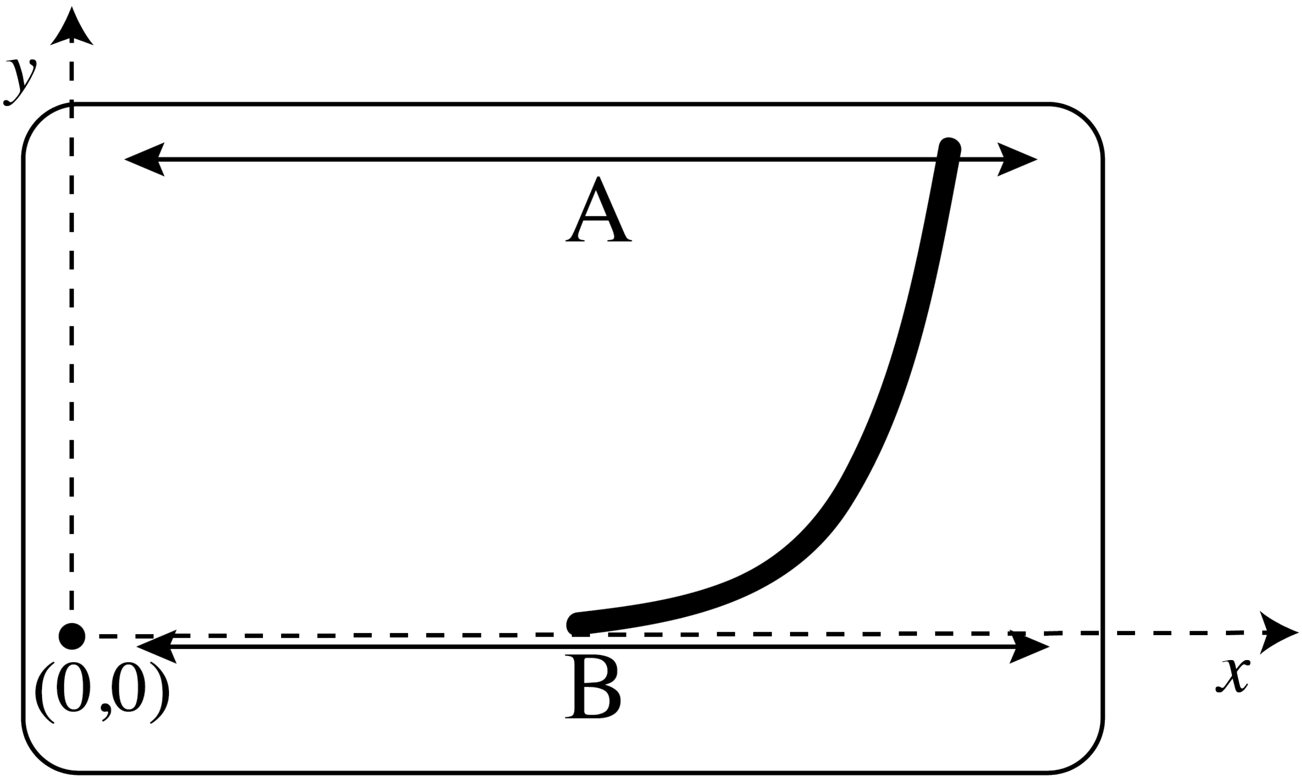
Here $\tan\theta = \frac{h}{l} = 0.103 \pm 0.006$, so $d = 0.103\ y$.

B.2

A – fastest at largest y.

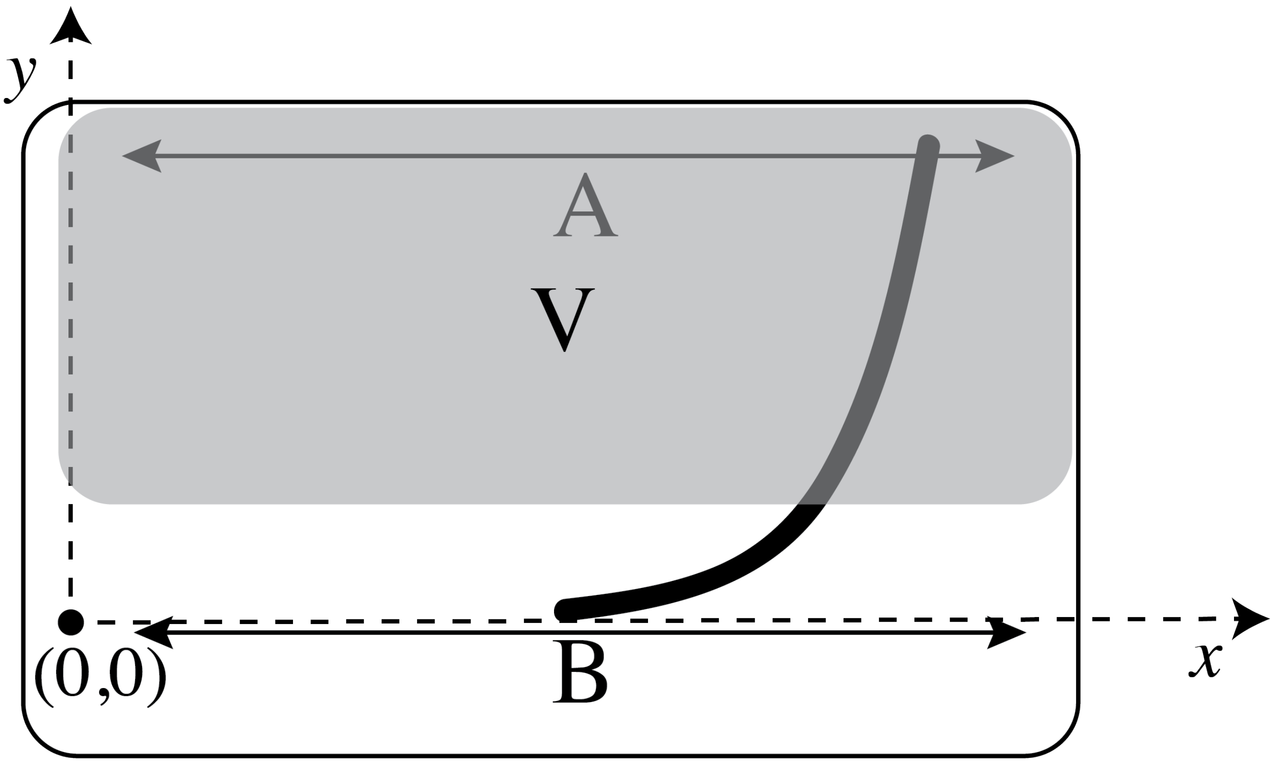


B – slowest at y=0.



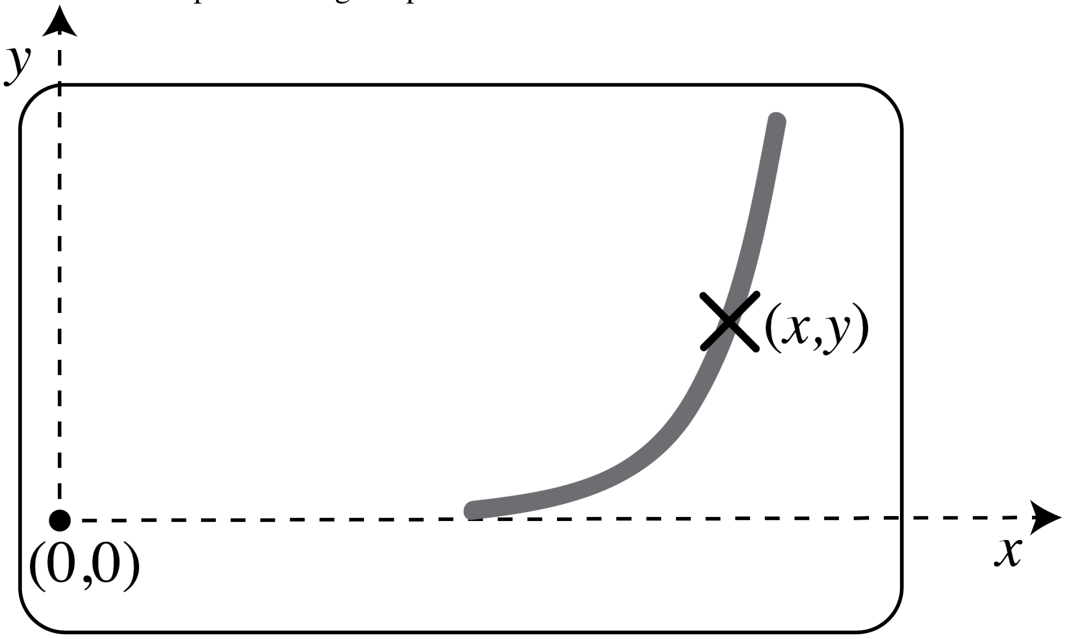
B.3 If x=0 when t=0, then $x = vt$, however, $v = \alpha\sqrt{d}$, so $x = \alpha\sqrt{d}t$.
Hence, $x = \alpha\sqrt{y \tan\theta}\, t$, or equivalently, $x^2 = \alpha^2 \tan\theta\, t^2 y$.
Here $\tan\theta = \frac{h}{l} = 0.103 \pm 0.006$, so $x = \alpha\sqrt{0.103y} \cdot t$.

This approximation will be least valid when the direction of propagation varies the most from the x-direction, and when the depth is least as there are nonlinear effects. Both of these happen for small y, in other words, $y < k$ for some constant k. This is shown as the grey shaded region marked V on the diagram below.



B.4 Diffuse light is more appropriate as the pulses are curved, so it is not possible to get direct reflections from the available source from enough of the pulse. See the second diagram on p. 1 for light position.

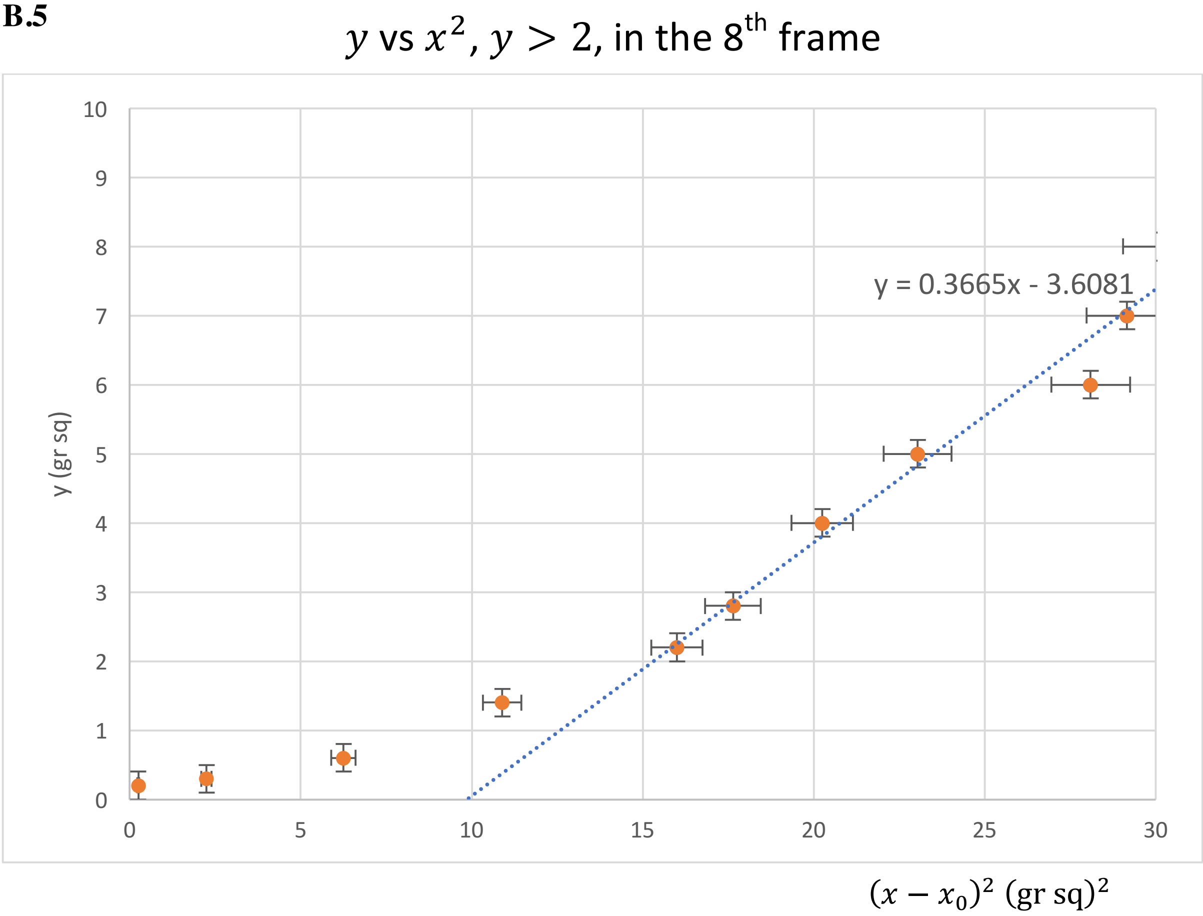
Videos of the curved pulses are recorded, with adjustments to the lighting, until a clearly visible pulse is observed near where the fastest travelling sections have reached the end. For that single frame the coordinates of points along the pulse are recorded.



The 8th frame after the generation of the pulse was used so $t = 8/25\ \mathrm{s}\ = 0.28\ s$.
Here x_0 is the x coordinate of the position where the pulse front is at y=0. This is treated as the new origin, and the offset in the $x = 0$ position is $x_0 = 4.5$ gr sq.

x (gr sq)	y (gr sq)	$(x - x_0)^2$ (gr sq)^2	$\Delta[(x - x_0)^2]$
5.0	0.2	0.25	0.02
6.0	0.3	2.25	0.15
7.0	0.6	6.3	0.4
7.8	1.4	10.9	0.6
8.5	2.2	16.0	0.8
8.7	2.8	17.6	0.8
9.0	4.0	20.3	0.9
9.3	5.0	23.0	1.0
9.8	6.0	28.1	1.1
10.0	8.0	30.3	1.2
9.9	7.0	29.2	1.2

B.5



Converting to SI units, the slope m = 0.280 /m.

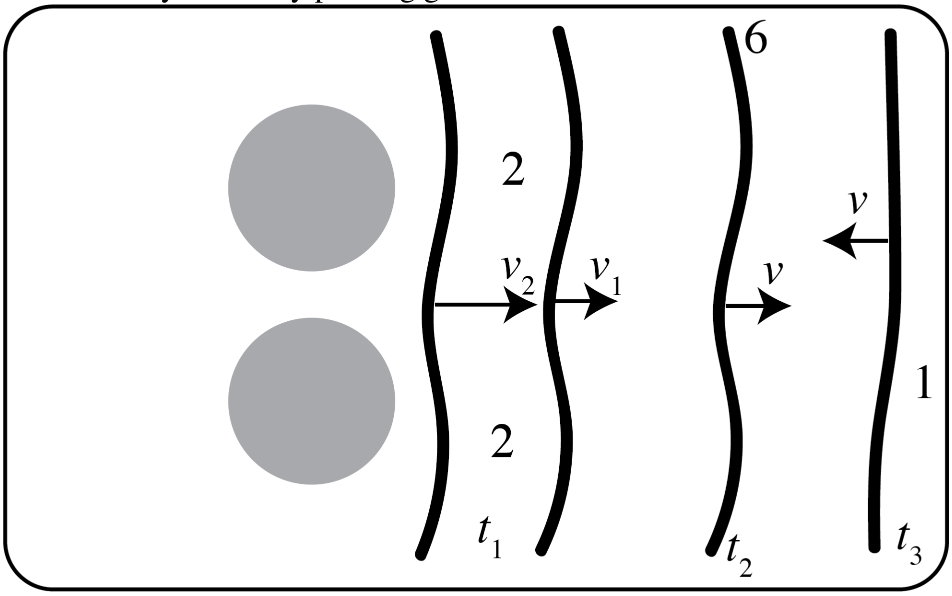
$$m = \alpha^2 \tan\theta\, t^2$$

Hence $\alpha = 5.9 \pm 0.5\ m^{1/2}s^{-1}$, and $v(d) = 5.9 \times \sqrt{d}$.

Uncertainty was calculated from the slope of the line of worst fit m = 0.331/m.

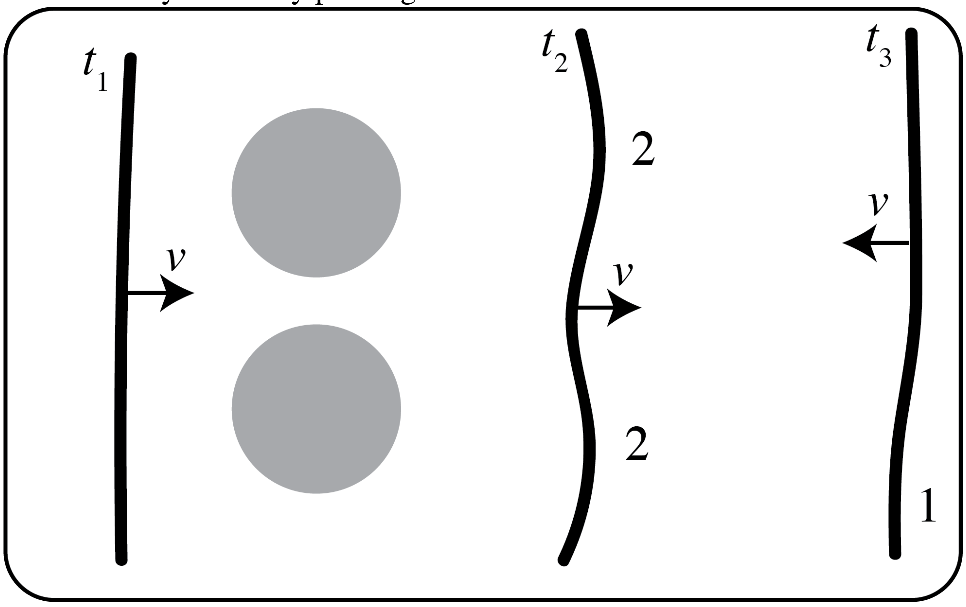
Part C Wave and magnetic effects

Mechanically driven by pushing glass



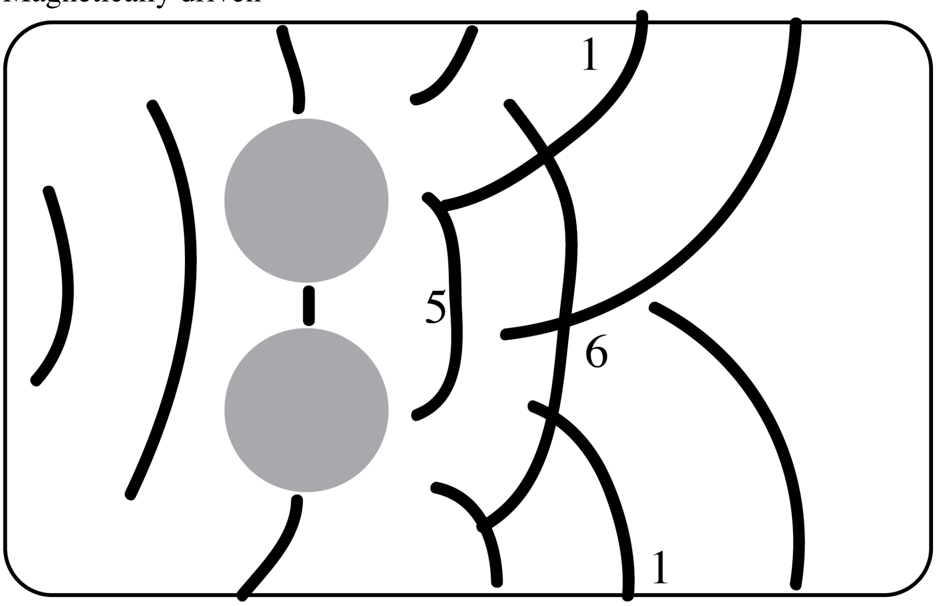
Refraction observed by perturbation of front over magnets,
Interference when the fronts meet,
Reflections from end.
$t_1 < t_2 < t_3$

Mechanically driven by pushing base



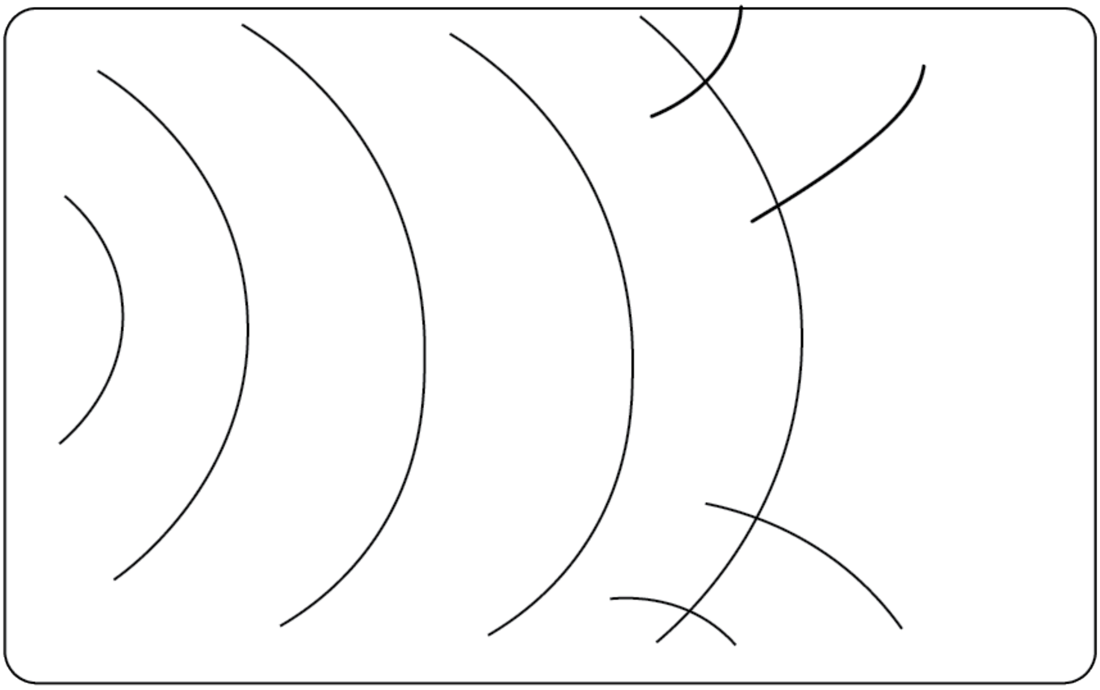
Refraction as wave is perturbed over the fronts,
Reflections from ends,
Maybe some diffraction after passing between the lumps over the magnets.
$t_1 < t_2 < t_3$

Magnetically driven



Reflections from side walls and ends
Diffraction after passing between the lumps.
Interference from many waves crossing.
Each line represents the position of a pulse front in a particular frame.

Part D Internal properties of ferrofluid within a strong magnetic field
D.1

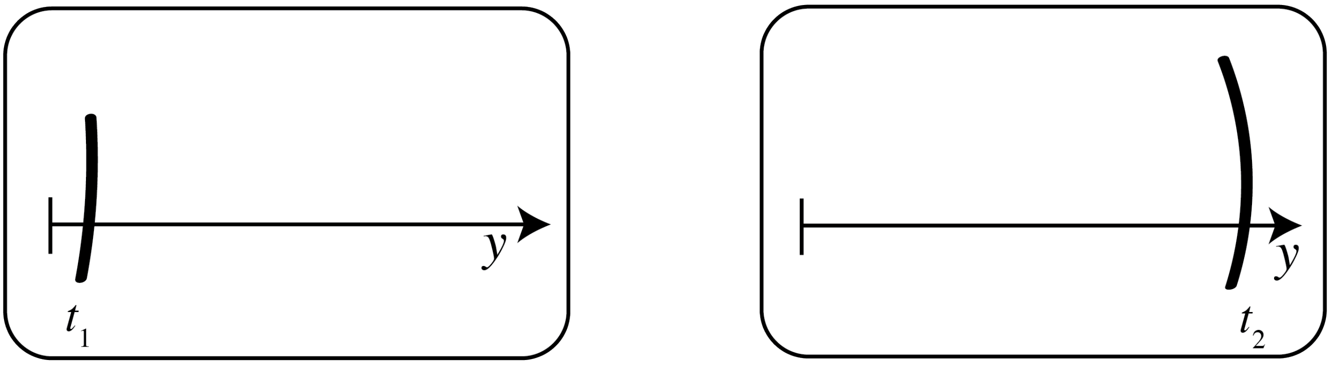


Magnetically driven pulses are not planar, so there is resulting reflection from the sides of the container. Note the multiple lines demonstrate the same pulse at different times.

D.2 Direct lighting, as in the first diagram on p. 1.

Speed measurements of the magnetically driven waves are around the same, to somewhat faster than small amplitude mechanically driven waves. Students should find that pulses are around 0.1-0.4 (gr sq)/m faster than in A2/3.

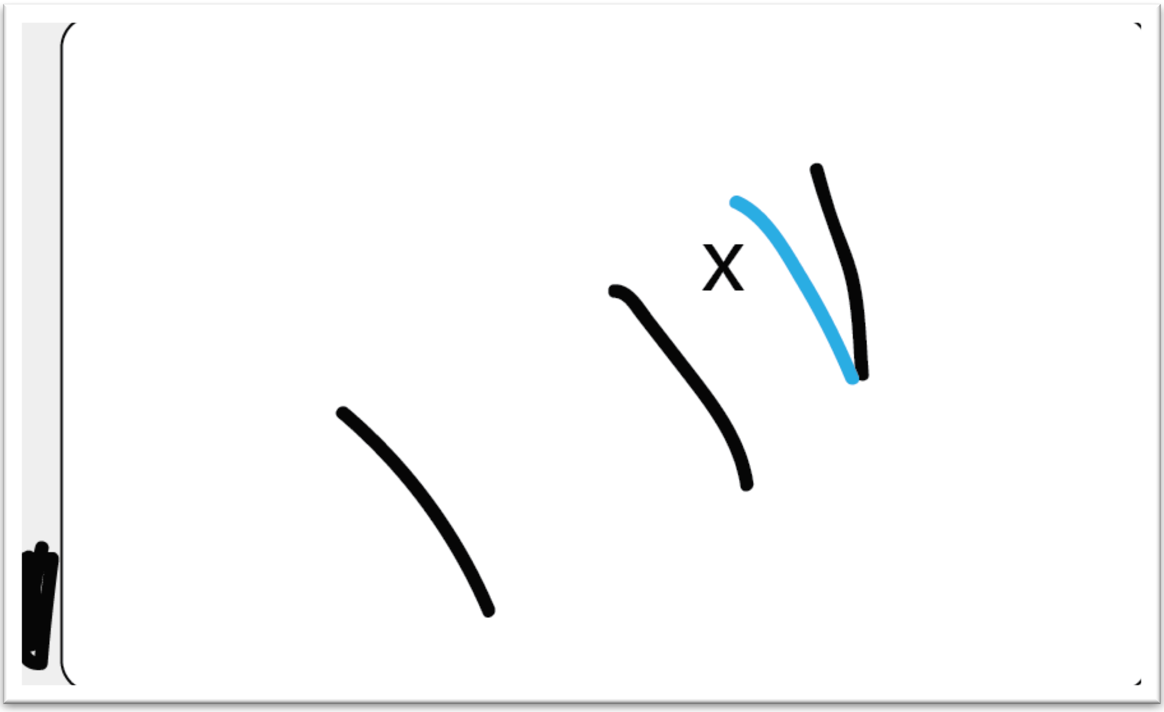
Data and sketches should look similar to A2/3 otherwise.



Measurements of the y position at two times, and the difference in the times allow calculation of the speed.

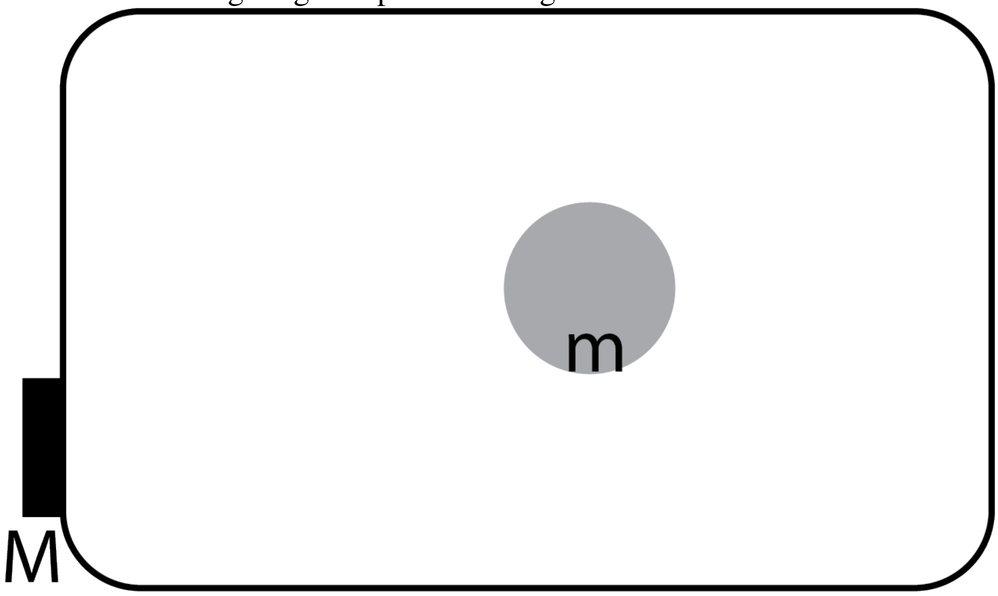
The height of the lump can be estimated by observing from the side, or more accurately by using the limiting value from E1 Part C.

D.3 The light was placed in the diffuse light set up. See the second figure on p.1.

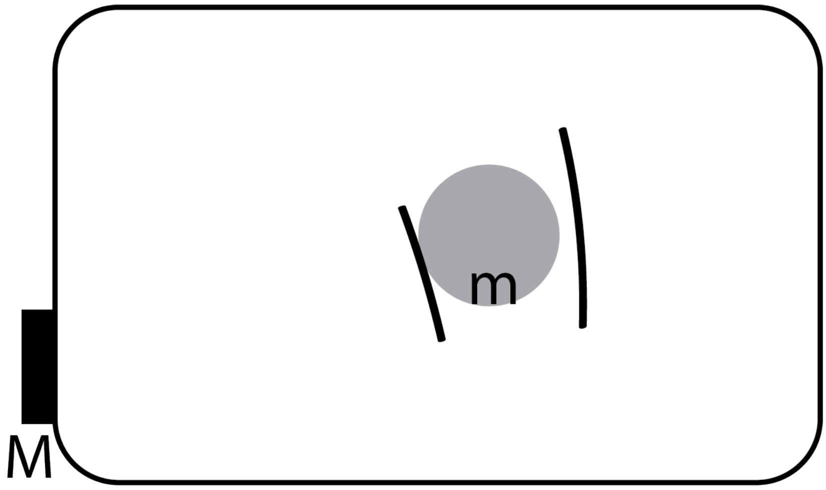


The black represents observed pulses over the magnet x. The blue represents the expected positionsing of the pulseafter travelled that distance.

D.4 The diffuse lighting set up was used again.



D.5
A wave front was observed to travel as additional 0.8 gr sq over 8 frames. The extent of the lump is assumed to be 3cm in diameter and the additional distance in the time all occurs over the lump. The wave crossed the lump in around 2 frames This means that the wave travels at a speed of around 0.35 m/s over the lump.



The two wavefronts shown above are only 2 frames apart.
Measurements of position were taken when the wavefronts where further apart.

D.6 The height of the lump can be estimated by observing from the side, or more accurately by using the limiting value from E1 Part C.
The best estimate of the height of the lump is found to be 5mm. The expected speed of fluid of depth 9mm, compared to fluid of depth 4mm is $\sqrt{\frac{9}{4}} = \frac{3}{2}$ times larger, which is $\frac{3}{2} \times 0.26 \frac{m}{s} = 0.39\ m/s$.

As these are estimates they are close enough that we cannot conlcude that the change in wave speed is due to anything other than the additional depth of the fluid.

E1. Static response of a magnetically active fluid
Marking scheme. Version 1.5a

Question part	Total marks	Partial marks	Explanation for partial marks and special cases
A.1	0.8	0.1 0.5 (0.2) 0.2	Diagram of a useful setup Full marks for z within range (0.070 ± 0.003)m For z within range (0.07 ± 0.01)m Uncertainty estimate (reasonable, <= 35%); if 2mm 0.1
A.2	0.8	0.3 (-0.1) (-0.1) 0.3 0.2	Correct formula $\Delta\rho g = 3\chi B_r^2 a^4 l^2/(8\mu_0 z^7)$ If measured a or l incorrectly instead of using given value (if good measurement of a or l, give full points) If $\Delta\rho$ out by ~10 but dimensionally correct No marks if dimensionally incorrect (eg. no g) Value of $\Delta\rho$=4.1 kg· m^{-3} (e.c.f. full marks for wrong z in A.1 – see figure) Uncertainty estimate (1.2 kg· m^{-3})
B.1	0.6	0.2 0.1 0.2 0.1	Value for $z_{crit} = 41 \pm 1$mm (or 22 ± 1mm full points using small magnet) Uncertainty for z_{crit} at most 2mm Value for $\lambda = 10 \pm 1$ mm Uncertainty for λ at most 2mm
B.2	0.6	0.3 0.2 0.1	Value for $\sigma = 1.0 \cdot 10^{-4}\ N \cdot m^{-1}$, correct with an order of magnitude (e.c.f. -0.1 for wrong Δ) Uncertainty estimate $\frac{\Delta\sigma}{\sigma} = \frac{7\Delta z}{z} + \frac{2\Delta\lambda}{\lambda}$ Relative uncertainty less than 70%
C.1	0.6	0.2 0.2 0.1 0.1	Diagram of a useful setup – needs to show clearly the measured quantity and the setup Measurements (at least 3) and calculations (0.1 for 1 measurement giving good value of for Δz) Value for $\Delta z = 0.80 \pm 0.02$ mm Uncertainty estimate <3%
C.2	3.5	1.0 0.5 0.3 0.7 0.5 0.5	Raw measurements for # of turns and M (1.0 for 18+ data points, 0.2 per 4 data points if <18, no points for changing l) Correct conversion to R Graph shows both regions Graph has 18+ correct data points (or if not 18+, 0.2 per 6 data points, plotted correctly) Good fit to correct region Answer n with range 6 -- 7 with uncertainty
D.1	0.5	0.5	Value for $\sigma = 1.1 \cdot 10^{-2} N\ m^{-1}$ • Full mark if within 30%, 0.2 – within 50%, else – 0
D.2	1.0	0.9 (0.6) (0.4) 0.1	5+ up, 6+ down 5+ up, 5+ down 4+ up, 4+ down No points if only in one direction Reasonable uncertainty estimate
D.3	1.0	0.3 (-0.1) (-0.1)	Correctly plotted graph No error bars if uncertainty in D2 large enough to plot Only one direction

		0.2 0.2 0.3	One smooth curve fitting points Second smooth curve fitting points Clear hysteresis shown: at least 1.5 mm separation in z (0.1 if separated by less, 0 if lines cross)
D.4	0.6	0.2 0.2 0.2	Correct graph for surface energy Correct graph for magnetic energy Correct step behavior for both graphs

Experiment
Q2 Wave pulses in a magnetically active fluid
Marking Scheme

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				TOTALS
A1	0.3	0.1	Ferrofluid in container	1.3
		0.1	Light position and direction shown	
		0.1	Incudes at least one of camera, wooden base and hand to drive pulses	
A2	0.8	0.2	Sketch at least one pair of frames with important features and measurements	
		0.2	3 data points, raw data (0.1 for 2 data points)	
		0.2	Calculate speed in m/s - including converting from whatever units were measured in the video	
		0.2	$v = 0.25 - 0.30\ \mathrm{m/s}$	
A3	0.2	0.1	Reasonable approach/formula	
		0.1	Up to 15% and consistent with method used.	
B1	0.3	0.1	Diagram	3.4
		0.1	Measurements of h and l - no uncertainties no mark	
		0.1	$d(y) = y\tan\theta$ in terms of measured value of $\tan\theta$	
B2	0.3	0.1	A + B marked	
		0.1	Curve shape	
		0.1	Origin and axis orientation indicated somehow.	
B3	0.3	0.2	Relationship	
		0.1	V marked on B2 diagram	
B4	1.2	0.2	Diagram including set up for diffuse lighting	
		0.2	Choosing to fix t, as there is higher resolution in x and y	
		0.4	At least 10 coordinate pairs (0.2 for 6 coordinate pairs, 0.1 4 coordinate pairs)	
		0.2	Uncertainties on data	
		0.2	Sketch of key frame with curve and coordinates marked	
B5	1.3	0.1	Convert to SI units	
		0.1	Choice of origin - $x = 0$ is not the edge of the container	
		0.1	Calculations of values to graph	
		0.4	Useful graph, accurate plotting, suitable labels (0.2 if t is not fixed on graph)	
		0.2	Uncertainties calculated and graphed	
		0.2	$\kappa = 4 - 7\ m^{1/2}s^{-1}$	
		0.1	Calculation of uncertainties	
		0.1	Uncertainty less than 15%	

C1	1.8	0.2	Sketch - showing two pulses, one catching the one in front, with perturbations around magnets	1.8
		0.3	2. over magnets, 6D. when fronts catch each other, 1. reflection off ends	
		0.2	Sketch - one pulse being refracted by two magnets	
		0.3	2. over magnets, 1. reflection off ends, 5. diffraction through gap	
		0.4	Sketch - sidewall reflection, lump refraction, interference everywhere, diffraction between lumps	
		0.4	1, 2, 5, 6d	
D1	0.2	0.2	More circular shape, and reflection off walls	3.5
D2	0.8	0.1	Diagram of set up, similar to A	
		0.1	Sketch at least one pair of frames with important features and measurements	
		0.2	3 data points, raw data	
		0.1	Calculations	
		0.1	Uncertainty in speeds	
		0.2	Speeds in range 0.26-0.31 m/s	
D3	0.4	0.2	Sketch with similar form to D1 before where the pulse crosses the region with the magnet	
		0.2	In region where it has crossed the magnet pulse should be ahead of where it would otherwise be	
D4	0.3	0.1	Diffuse lighting (or direct lighting, but only if the sketches of frames demonstrate it was appropriately aligned).	
		0.1	Graticule aligned with wave propagation direction.	
		0.1	Wooden base, fluid and magnets marked.	
D5	1	0.2	Sketches of frames with magnet lump region identified.	
		0.2	At least 3 data sets.	
		0.1	Calculations of time from frames	
		0.4	Time is in range 0.06 to 0.12 s	
		0.1	Uncertainty in time	
D6	0.8	0.1	Simple model of lump, e.g. cylinder.	
		0.3	Good estimates of dimensions of lump and depth of bulk fluid,	
		0.2	Calculation	
		0.2	Conclusion - probably ambiguous.	
			TOTAL:	10