**SL100B**
**Instructions**

Congratulations on your purchase of the SL100B. The following instructions will guide you through the setup and operation of the unit. It is strongly recommended that you read through the instructions thoroughly before attempting to use the equipment

**Introduction**

Single bubble sonoluminescence, hereafter abbreviated SL, was discovered in the late 1980's and has since received a great deal of attention. This remarkable process involves, at its core, trapping a gas bubble at a sonic antinode location in a resonance mode of a cell. The exact geometry of the cell is not important but it is necessary that there exist a spatial pressure gradient in order for the bubble to be positionaly stabilized. In the presence of the alternating cycle of acoustic pressure the bubble expands and collapses. When the amplitude of the pressure becomes large enough the collapse of the bubble enters a new regime in which the radius collapses to its hard core limit heating up the gas contents inside and emitting a very brief but copious amount of light. This light can be seen with the unaided eye. Although the emission mechanism along with a number of other properties of SL are still not fully understood, the basic hydrodynamic equations governing the gross motion of the bubble have been around for quite some time and do accurately describe over 99.9% of the bubble's motion. The Rayleigh Plessett equation shown below has been used extensively to describe the motion of the bubble in its many regimes.

Eq(1)

$$-R\ddot{R}\left(1-\frac{2\dot{R}}{c}\right)-\frac{3}{2}\left(\frac{d^2R}{dt^2}\right)^2\left(1-\frac{4\dot{R}}{3c}\right)+\frac{P(R,t)}{\rho}+\frac{R}{c}\frac{dP(R,t)}{dt}-\frac{P_a(0,t)}{\rho}-\frac{R}{\rho c}\frac{dP_a(0,t)}{dt}-\frac{P_o}{\rho}=0$$

with the boundary condition at the fluid gas interface given by

$$P(R,t)+\frac{4\eta\dot{R}}{R}+\frac{2\sigma}{R}=P_g(R,t)$$

and the use of a van der Waals hard core $a$ in the ideal gas law to give a gas pressure $P_g$

$$P_g(R)=\frac{P_oR_o^{3\gamma}}{\left(R^3-a^3\right)}$$

where $R$ is the bubble radius, $c$ is the speed of sound in the fluid, $\rho$ is the density, $\eta$ is the viscosity, $\sigma$ is the surface tension, $P_a$ is the acoustic pressure, and $P_o$ is the ambient pressure.

A graph of the bubble radius and driving amplitude as a function of time is shown in Figure 1. This graph was generated by a numerical integration of Eq. 1.

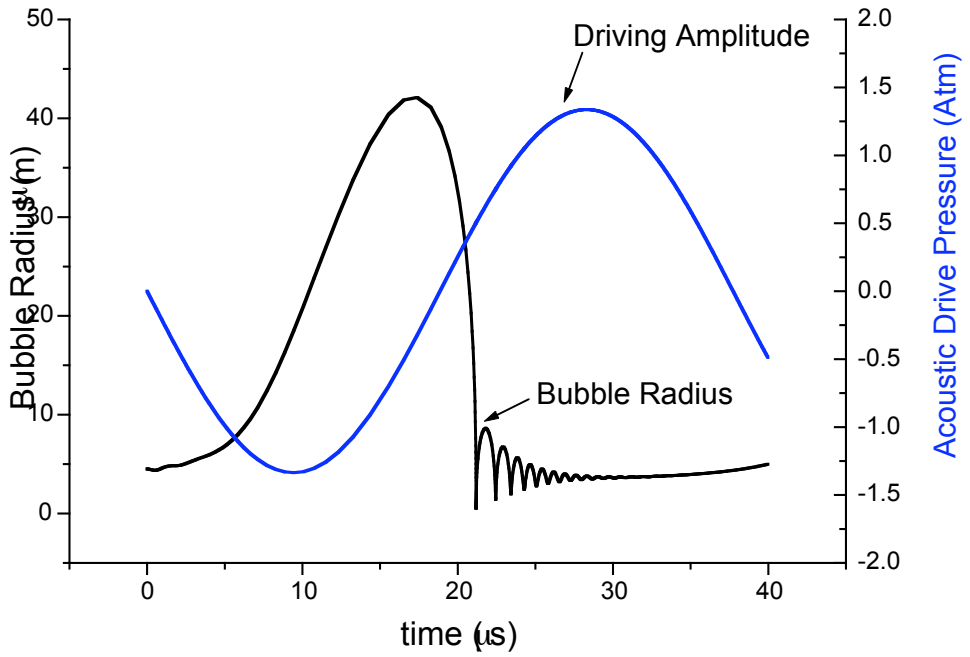



Figure 1

Among the first properties that were observed was the very brief nature of the light emission. Initial measurements using high speed photomultiplier tubes placed an upper limit of 50 ps on the emission time. Recent measurements using time correlated photon counting techniques have shown a diversity of emission times depending on the gas contents, with some emission times as long as 350 ps. Another observed property was the enhancement of the light emission by the doping of the water with a small concentration of noble gases such as Ne, Ar, and Xe. It was also observed that that cooling the liquid to near freezing resulted in an increase in light emission by a factor of six.

**The Instrument**

The apparatus consists of

- Ultrasonic Horn
- Rectangular Cell
- Control Box
- Degassing Flask & Connecting cables

In order to set up a standing acoustic wave in the cell it is necessary to deliver acoustic power with sufficient amplitude to the volume of water. This is accomplished with the ultrasonic horn. Internally the horn contains a series of annular shaped disc transducers which are bolted into its base. The basic structure and shape of the horn is designed to efficiently couple the pressure waves generated from the transducers to the narrow stem of the horn. All of the transducers are the same. They consist of a ceramic material which has been prepared in such a manner to have a permanent polarization. In other words what we

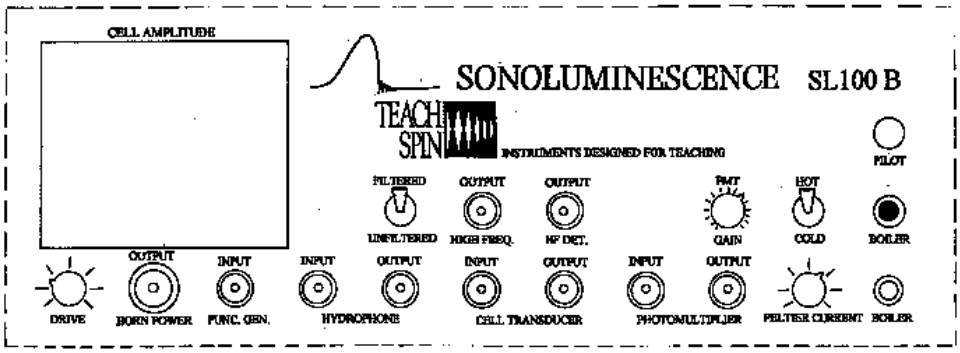
have is a specialized capacitor. As a charge is placed across this capacitor there is a force generated across the ends, as the capacitor wants to separate. Since the transducers are compressed, this repulsive force does not physically expand the disc but does produce a dynamic pressure. As the charge across the transducer is reversed there is now an attractive force which results in a negative pressure amplitude.

In order to achieve the desired pressure levels, six of these transducers are placed one on top of another and connected electrically in parallel. Acoustically this is equivalent to connecting the devices in series. Collectively the 6 ceramic disc capacitors have a total combined capacitance of approximately 11 nF. In order to efficiently couple electrical power into the transducers, it is advantageous to connect an inductor in series to achieve electrical resonance as given by the simple formulation $\omega L = 1/\omega C$.

The cell is a plastic container onto which is epoxied a small ceramic transducer that serves as a microphone. Since this transducer is not compressed small fluctuations in its diameter produce a measurable signal. By attaching this transducer to the bottom of the rectangular cell one can easily detect when the pressure in the cell is in resonance. The cell also contains a small NiCr filament wire that connects to the front panel of the control box. A bubble is seeded when a current is passed through this filament momentarily causing many vapor bubbles to be formed which then coalesce into a single bubble which is trapped at the closest pressure anti node.

At the end of the case that houses the cell are 3 connectors located on a brass plate. At the bottom is a BNC connector that is attached to the ceramic microphone transducer on the cell. Above this connector is a 5.1 mm power jack that connects to the optional PMT. This connection should only be made when the PMT power is off. At the top is a 5 pin Neutrik connector that attaches via the thick gray cable to the back of the control box to an identical connector. This cable carries the current to the optional Peltier cooled module, the current to the fan, and the adjustable power to the PMT.

The SL100B employs a 3mH inductor in order to impedance match the capacitor at a frequency of 27 KHz. For frequencies significantly above or below this value of the inductance should be changed, if it is found that there is not enough power being coupled into the horn. Inductors can be purchased from a number of electrical suppliers with values in the range of 0.5 mH to over 20 mH.




**Control Panel**

The control box is the heart of all the signal processing of the system. Going from right to left the front panel can be divided into six sections the drive, the hydrophone, the cell, the photomultiplier, the Peltier cooler, and the boiler. Each of these sections will be outlined below. All signal connections are made via BNC cable with the exception of the power to the ultrasonic horn which utilizes a TNC connection.

1. **HORN DRIVE**

The control box primarily has a high voltage amplifier that is used to drive horn. In addition there are a number of circuits that perform specific function depending on what options are being employed. At the far left is a control knob that adjusts the drive level sent to the cell. Next to the drive control is **HORN POWER OUTPUT** this uses the special TNC connector which can only be connected to the matching connector on the horn. Next to the is **HORN POWER OUTPUT** is the input for the function generator labeled **INPUT FUNC. GEN.** This input connects a sine wave from an external function generator to the internal amplifier in the control box.

2. **HYDROPHONE**

The next section is labeled on the bottom **HYDROPHONE** and contains 2 BNC connectors as well as a switch. The first connector labeled **INPUT** is the input from the hydrophone. The 2nd BNC connector is labeled **OUTPUT** of which 2 modes are available filtered or unfiltered. Both outputs are subjected to a first order high pass filter with a corner

frequency of 4 KHz; this is employed to filter out unwanted 60 Hz line noise. The **FILTERED** output passes the hydrophone signal through an additional $5^{th}$ order high pass filter with a corner frequency of 150 KHz. This allows the user to see only the small high frequency component that is present ***when a bubble is trapped***. The **UNFILTERED** output simple passes the original signal into the 4 KHz high pass filter and then directly to the output.

### 3. **CELL TRANSDUCER**

The next section contains four BNC connectors and is labeled at the bottom **CELL TRANSDUCER**. The connector in the bottom left quadrant is labeled **INPUT** and accepts the input signal from the transducer attached to the cell. After the input the signal is passed through a $1^{st}$ order high pass filter with a corner frequency of 4 KHz, with the purpose of filtering off unwanted 60 Hz line noise it then goes to other stages which process the signal further. The next 3 connectors are outputs which have processed the signal in a different manner. To the right of the input connector in the lower right quadrant is the **OUTPUT** which simply passes the comlete signal directly to the output. This allows one to view signal produced from the transducer which contains the fundamental as well as the high frequency component that is present when a bubble is trapped. This output is used most often as it allows continous viewing of a single signal that contains information on the level of acoustic drive pressure in the system as well as the magnitude of acoustic emission from a trapped bubble. The next output is labeled **HIGH FREQ. OUTPUT** and just like its counterpart in the hydrophone section filteres the signal from the cell transducer with a $5^{th}$ order high pass filter with a corner frequency of 150 KHz. The last connector located in the upper right quadrant is labeled **HF DET. OUTPUT** and simply uses peak detector to measure the maximum level of the high frequency output. This peak detector has a 0.1 s time constant which allows the output to change as the average overall peak value changes with driving amplitude or frequency but will not change over a single period of the acoustic frequency.

### 4. **PHOTOMULTIPLIER**

The fourth section is the **PHOTOMULTIPLIER** section. This section contains 2 BNC connectors as well as a control knob and an LED. This first BNC connector just below the LED is labeled **INPUT** and simply feeds the input from the PMT to a buffer amplifier. The impedance that this section presents to the PMT is 10K Ohm. This value was selected to give an appropriate time constant. The $2^{nd}$ BNC connector labeled **OUTPUT** carries the output of a peak detector. Just like the other peak detectors in this unit the time constant is 0.1 s but unlike the other peak detectors the peak voltage is negative (since this is polarity of the PMT). Above the output connector is a control knob that is labeled **PMT GAIN** this control knob contains *both* a switch as well as an adjustment for the PMT output voltage. The switch is engaged off when the knob is turned fully counterclockwise, when it is turned clockwise it engages a relay that physically connects the output from the internal voltage to the connector in the back of the unit. The relay also turns on the LED indicating the PMT is receiving power. The voltage is continuously adjustable from 0 to 7 volts. Next to the control knob on the left is an LED indicating when the switch has been turned on.

## 5. **PELTIER COOLER**

In the next section are the controls for the Peltier cooler. When using this option, a separate cell is employed that contains a thermoelectric cooler. When a current is passed through the thermoelectric heat is transferred from one side of the cooler to the other causing one side to cool off and the other to heat up. The control knob labeled **PELTIER CURRENT** adjusts the current going into the cooler module allowing one to adjust the amount of cooling. Above the control knob is a switch labeled **Direct** and **Variable** when the switch is thrown to the **Variable** position, the extent of the bottom surface cooling is controlled by the control knob and when the switch is positioned in the **Direct** position the Peltier controlling circuitry is bypassed and the Cooler is run at maximum current. Under normal operation when sustained cooling is desired the switch should be in the **Direct** position. Turning the control knob all the way counterclockwise turns off the entire Thermoelectric circuitry.

## 6. **BOILER**

The last section at the far right contains a phono jack output labeled **BOILER.** The filament wire is connected here. Above this jack is a pushbutton switch also labeled **BOILER** which is pressed momentarily when a bubble is to be seeded.

### Getting Started

Fill the cell with degassed water. If you need instructions on how to prepare a sample of degassed water go directly to that section (page 10).

This first section will explain the basic connections needed to set up the system to trap a bubble in sonoluminescencing. Once these skills are mastered then one can proceed to the later sections that describe using the hydrophone, PMT and Peltier cooler functions.

### Connecting the horn

First connect the cable from the ultrasonic horn to the threaded TNC connector on the far left end of the unit. Make certain that the power is turned off and the volume control knob is turned all the way down. Insert the long 18 inch aluminum rod into the flange mount on the box that contains the cell and tighten, using an Allen wrench. Next secure one end of the T clamp onto the rod that extends out from the horn and slide the other end of the T clamp onto the long rod attached to the box. Adjust both the vertical and horizontal position of the horn such that the stem of the horn dips into the water approximately 5 mm and tighten the screws on the clamp.

### Adjusting the amplitude from the frequency generator

The SL100B uses its own internal volume control to adjust the power sent to the horn. The system is designed to accept a signal level of 1 V peak amplitude (2 V peal to peak) from an external frequency generator. If a voltage larger than this were used than at large amplitudes the output from the internal power amplifier to the horn would “clip” producing spurious distortion which could damage the transducers.

Turn on the main control box using the switch located on the back of the unit in the power entry module, you should see a red led on the right side of the unit light up indicating the unit is turned on. Using either the Ramsey function generator or another similar model connect the output from the function generator to the input labeled **cell input** (***note this connection is only temporary to adjust the volume level of the frequency generator***). Set the frequency to a value of 27 KHz and adjust the volume from the frequency generator until the level of the analog display reads 4 volts. We are temporarily using the cell input to display the voltage level of the frequency generator. This input has a high pass filter that rolls off around 4 kHz to eliminate 60 Hz noise (hence we use a frequency of 27 kHz) and a gain of 4 thus a reading of 4 volts on the analog display indicates a peak voltage of 1 volt. Once this voltage level has been adjusted disconnect the frequency generator from the **CELL TRANSDUCER INPUT** and connect it to the **FUNC GEN** input.

**Connecting the Cell Input**

With the horn and frequency generator connected now attach a BNC cable from the cell to the input on the control box labeled **CELL TRANSDUCER INPUT.** This input is connected to a pill transducer epoxied to the bottom of the cell. This transducer picks up the signal produced by the standing waves in the water as well as the acoustic signature of a trapped bubble. When a bubble is trapped both signals are superimposed. The input of the pill signal to the control box is sent to a buffer that filters off any 60Hz line noise that may be present on the signal and then passes it to an output labeled **CELL TRANSDUCER OUTPUT.** The signal is also sent to a peak detector where its peak value is amplified by a factor of 4 and sent to the analog display on the from of the control box. This allows one to adjust the frequency and simply look at the value on the display labeled **CELL TRANSDUCER HF DET OUTPUT** to determine when one has passed through a resonance mode of the cell. For the first time user it is highly recommended that you use the optional output to the oscilloscope. This will allow you to actually see the signal as you pass through resonance and get a "feel" for how the acoustic signature looks of a trapped bubble.

**Connecting the boiler filament**

The boiler filament is a small piece of NiCr wire that has been coiled up and attached to the ends of a piece of stranded wire. DO NOT depress the boiler button unless the coiled end of the wire is submerged in water. Doing so will burn out the filament. One end of the filament wire contains an audio power jack, insert this end into the socket labeled **BOILER.** Place a bend in the filament end of the wire approximately 5-6 inches from the end such that the wire may be placed over the side of the cell with the filament hanging just off the bottom of the cell. The exact placement of the filament is not critical for these experiments.

**Finding the resonance**

Now you will locate the frequency at which the amplitude has a maximum response. Recall the formulation of the wave equation $\nabla^2 P = \frac{1}{c^2}\frac{\partial^2 P}{dt^2}$. In rectilinear systems the solution is in the form

$$P = X(x)Y(y)Z(z)\exp^{i\omega t}$$

where X,Y,and Z have the familiar forms

$$X = \begin{Bmatrix} \cos(k_x x) \\ \sin(k_x x) \end{Bmatrix}$$

$$Y = \begin{Bmatrix} \cos(k_y y) \\ \sin(k_y y) \end{Bmatrix}$$

$$Z = \begin{Bmatrix} \cos(k_z z) \\ \sin(k_z z) \end{Bmatrix}$$

The sin is chosen when the boundary is a pressure release (i.e. not rigid) and the cos is selected when the boundary is rigid and the velocity must be zero. The eigen frequencies are given by

$$f = \frac{c}{2\pi}\left[\left(\frac{n_x \pi}{L_x}\right)^2 + \left(\frac{n_y \pi}{L_y}\right)^2 + \left(\frac{n_z \pi}{L_z}\right)^2\right]^{1/2}$$

For the rectangular cell filled to approximately 10 cm, as indicated by the mark on the cell, the resonance frequency will be around 27-28 KHz in the [1,1,3] mode. Initially set the frequency to 26 KHz and the frequency increment (if available) to 10 Hz steps. Turn the control knob on the horn amplitude to the midpoint. You should see the needle on the analog scale move just a little. Slowly change the frequency while observing the amplitude on the meter and/or observing the amplitude directly on the oscilloscope. When you are near the resonance you will see the amplitude rapidly increase as you adjust the frequency, and then begin to decrease as you continue to increase the frequency. Finally adjust the frequency until the amplitude is near a maximum. You have now located the resonance peak of the cell. Depending on the condition of the water a typical cell should have a quality factor on the order of 100-200. Shown in Figure 3 is a calculated resonance peak for a resonance system with a Q of 95 as well as measured data from a rectangular cell in the [1,1,3] mode. Graph the peak amplitude as displayed on the analog panel as a function of driving frequency. You should obtain a curve similar to the one in Figure 3.

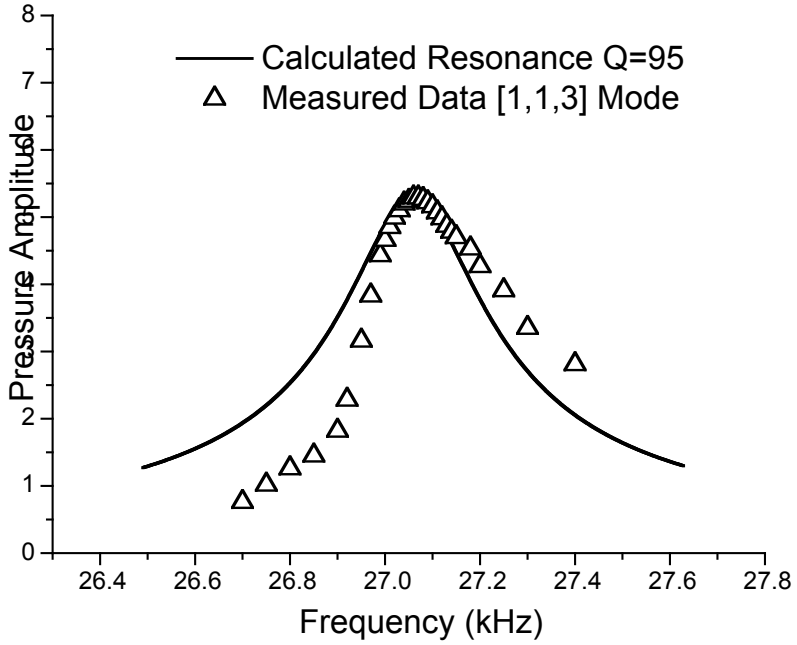



Figure 3

**Obtaining a bubble**

This next step is most crucial, as there is a certain degree of finesse associated with obtaining a bubble. The bubble has a fairly narrow range of amplitude in which it is stable. Thus if one is driving the system with too little or too much power a bubble will never be trapped. It is also recommended that for the first few times one uses this system an oscilloscope be used to aid in the trapping of a bubble. Remember that once a sample of water has been degassed it is generally good for about 2 hours thus you can not use the same batch of water the next day or even later the same day unless you degas it again.

Once the resonance has been found adjust the amplitude of the drive

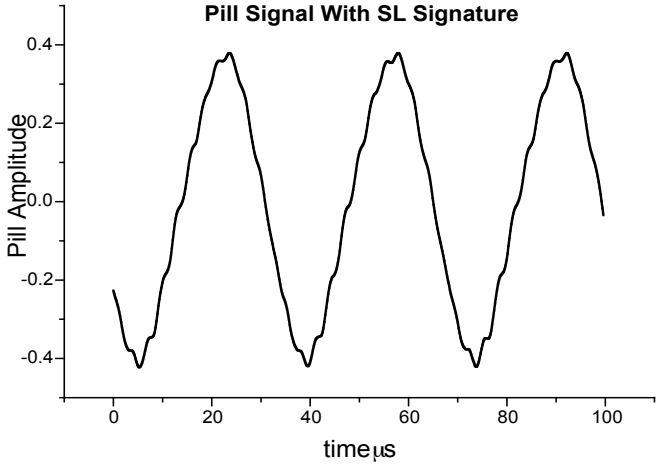


Figure 4

such that the meter reads 4 volts (this will correspond to 1 volt peak amplitude as seen on the oscilloscope). With the lights turned off in the room so that it is nearly pitch black briefly hit the boiler button to seed a bubble. You should hear a sharp zip as the water is boiled off and notice a momentary distortion of the pill signal as shown in Fig.4 (If you are also viewing this on an oscilloscope it is best to look at the oscilloscope and look for a distortion of the sine wave.)

When you have SL you should see a tiny blue light emanating from the lower portion of the cell
If you hit the boiler several times and you get no SL try lowering the amplitude by 10 to 20%. If this does not produce SL try raising the amplitude by 10 to 20%. Initially as the water heats up you will have to adjust the frequency constantly to maintain resonance. The bubble will frequently go out simply hit the boiler and seed another one as this happens.

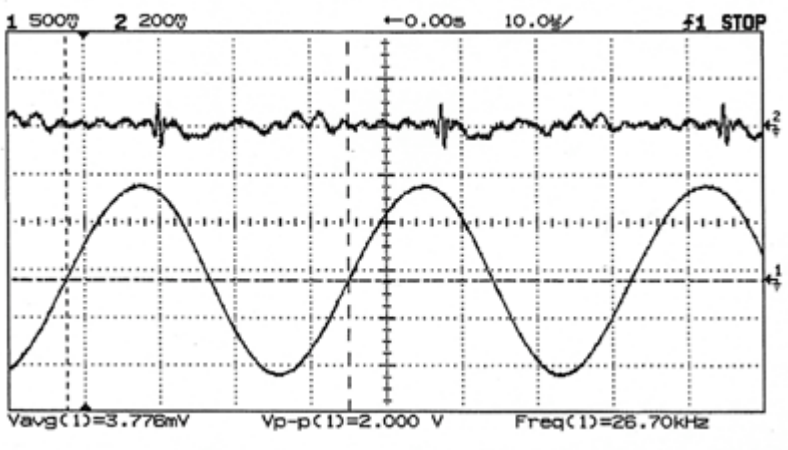



Figure 5

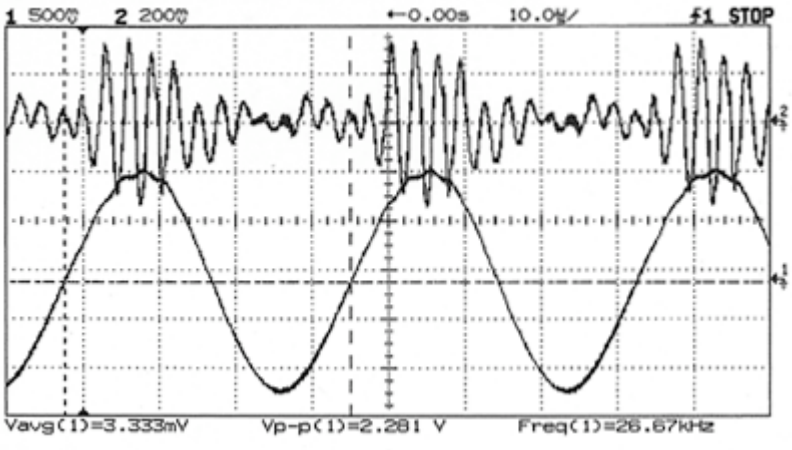



Figure 6

A few pointers about obtaining the bubble.
It is instructive to look at the distortion of the signal as seen on the oscilloscope as often when one is close in parameter space (i.e. the correct amplitude and frequency) to trapping a bubble the distortion will appear momentarily on the signal trace for a few seconds and then dissipate. If this is the case your amplitude may be just below or just above the threshold. The cell output labeled **HIGH FREQ** may be useful in observing the signature associated with a trapped bubble. The upper trace on Figure 5 shows the high frequency output when there is no trapped bubble. The upper trace in Figure 6 shows the signal when a trapped bubble is present. Careful inspection of the lower traces in Figures 5-6 will show the presence of this high frequency signature superimposed on the fundamental in Figure 6 but not on Figure 5.
Once a bubble has been trapped and then it disappears you may find it more difficult to re-trap at the same amplitude if you have already raised the amplitude while the bubble was shinning, in this case lower the amplitude slightly and then attempt to reseed the bubble.

**Degassing the water**
In order for the water to support a bubble it is necessary for the water to be partially degassed. The easiest method to degass the water which does not require the use of an external vacuum pump is to use the flask provided along with a hot plate and an ice bath. A "poor mans vacuum pump" will be employed. Fill the flask with distilled water and bring the water to a rolling boil for approximately ten minutes. This boiling action expunges most of the gas inside the water. After boiling for ten minutes immediately remove the flask from the hot plate and insert the rubber stopper with the attached valve into the top of the flask. Make certain that the valve is closed and the stopper is firmly pressed into the flask and insert the whole assembly into an ice bath for approximately one hour. During this time the water will cool but will not reabsorb an excessive amount of gas as the system is now sealed. The small amount of gas the water will absorb together with the cooling will generate a vacuum within the flask. After an hour or more has elapsed remove the flask from the ice bath and **slowly** open the valve; you should be able to hear the air now leaking back into the system. You water is now partially degassed and ready to be poured into the cell. An alternative method is to connect the flask with valve directly to a vacuum pump and allow the water to be pumped on for approximately 15-30 minutes. If this method is employed one should consider adding a desiccant between the flask and the vacuum pump as the water vapor will eventually erode away the mechanism inside the pump.

**Using the hydrophone**The optional hydrophone may be used to explore the nodal structure of the cell. Connect one end of the thin BNC cable to the **HYDROPHONE INPUT** jack and the other end of the cable to the end of the hydrophone with the pointed tip. The hydrophone's opposite end contains a high frequency probe which will measure the pressure amplitude at its surface. Connect a cable from the **HYDROPHONE OUTPUT** jack to an oscilloscope and set the toggle switch to **UNFILTERED.** This setting will allow both the low and high frequency components to be passed through the control box to the output.

To explore the 3 dimensional structure of the sound field in the [1,1,3] mode first tune the frequency to the appropriate value as

described in the section *Tuning the cell*. Begin with the bottom tip of the hydrophone in the center of the cell just off the bottom and slowly raise the hydrophone observing the peak amplitude of the signal. You should notice the signal passing through 3 maximums located at the respective pressure antinodes where it is possible to trap bubbles. With the probe located in the center at the 2nd pressure antinode move the probe across the horizontal directions and verify that as you approach the cell walls the pressure amplitude drops and the only maximum is in the center.

**Using the Photomultiplier (PMT)**

This section describes the basic operation of the optional PMT. **If this is your first time to use a PMT then you should read these instructions carefully as it is very easy to destroy a PMT with exposure to ambient light when powered up.** The basic architecture PMT utilizes a lens which contains a material that exhibits the photoelectric effect called the photocathode. When light strikes this lens low energy photoelectrons are emitted. Just behind the lens are a series of cusp shaped anodes which are held at successively higher potentials allowing electrons that are emitted from the previous anodes to be drawn to the next anode with a multiplication on the order of 5-10 occurring at each anode. In this manner a single photon which strikes the photocathode producing a single photoelectron will cause at the end of the cascade a current of approximately 1 billion electrons or about 1 nA of current which is easily measured. By controlling the overall potential across the successive anodes the gain of the device can be adjusted. Typically the total voltage across the entire anode cascade is on the order of 1-3 KV. Exposure of the PMT even momentarily to a small amount of room light would cause a tremendous amount of current to flow through the anode stages thus destroying the tube. It is thus of paramount importance that one **Never have power applied to the PMT when the tube is exposed to ambient light.**

The PMT utilized in the SL100B contains an internal power supply that delivers a maximum potential of 1200V across the anodes. This unit requires only an external voltage of 0-8 V (that is supplied from the control box) then amplified by a factor of 150 to generate the appropriate voltage internally. The control box contains a knob which when turned completely in the counter clockwise direction mechanically switches off the power to the tube. An LED indicator light above the knob illuminates when the switch is connected and the unit is powered up. Whenever you are handling the PMT always make sure the switch is turned all the way off and the indicator light is off. The PMT contains 2 leads one with a power jack that plugs into the cell box and another with a BNC connector that carries the signal. You will most likely want to connect an extension cable from the PMT signal to the control box. Since the control box, signal generator and oscilloscope produce a fair enough light to perturb the signal from the PMT you may wish to erect a light tight structure around the cell and PMT or simply cover the apparatus with some black felt.

Position the PMT such that the side containing the photocathode is several inches away from the bubble. Checking to make sure the PMT power is turned off plug in the PMT power cord into the 5.5 mm power jack located on the end of the box that houses the cell. You will also need to have the thick gray cable with the 5 pin Neutrik connector plugged into the back of the control console and the box housing the

cell. Initially connect the signal output from the PMT to the input of the control box marked **PHOTOMULTIPLIERT IN** using a T connector provided with the PMT. This configuration allows one to take advantage of the 10 K Ohm input impedance the control box presents to the PMT signal. The other end of the T connector should be connected to an oscilloscope (if available). The signal from the PMT will be a negative pulse with a relatively long recovery time so adjust the triggering accordingly. With the PMT shielded from ambient light slowly turn on the power to the PMT and adjust the control voltage until a signal appears. The time it takes the signal to go from 10% if its initial value to 90% of its maximum negative value is known as the rise time and is always much shorter than the recovery time (the time it takes the signal to settle back to 0). The light output per flash corresponds to the maximum negative amplitude produced on the oscilloscope trace.

A simple measurement of this maximum peak negative voltage is made within the control console and output as a DC voltage. This voltage may be measured using a simple multimeter. Adjust the amplitude on the horn volume and verify that the light emission from the bubble is a function of the drive level. You may also adjust the driving frequency and verify that on each side of the acoustical resonance peak the light emission falls off. In the [1,1,3] mode if you are able to generate 2 bubbles, one on the bottom and another in the middle, you will see on the oscilloscope 2 flashes per cycle 180 degrees out of phase with each other.

One of the most interesting properties of SL is its very short emission time. The emission time is much shorter than the temporal resolution of the PMT, so you will not be able to make a direct measurement of the flash width. But you will be able to se an upper limit on the emission time. To perform this portion of the experiment an oscilloscope of sufficiently high bandwidth is required with a digital oscilloscope the preferred option. Any system which acts on a signal, including an oscilloscope is characterized by its inherent bandwidth which is related to its rise time by the simple formulation $BW \cong 0.35/\tau_r$ with the rise time of the scope denoted by $\tau_{scope}$, the rise time of the PMT denoted by $\tau_{scope}$ and the flash width of the pulse denoted by $\tau_{SL}$. The overall measured time of the flash is given by adding all of the respective rise times in quadrature $\tau_{measured} = \sqrt{\tau_{SL}^2 + \tau_{scope}^2 + \tau_{PMT}^2}$. From a knowledge of the scopes rise time and the stated rise time of the PMT from the manufacturer one can place an upper limit on the flash duration based on the value of $\tau_{measured}$.

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