Measurement Notes

Note 60

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Subnanosecond Sample Holder

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Abstract

This paper discusses the design of a test chamber for biological samples. The time scale of interest is for pulse widths of the order of a hundred picoseconds or so.

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1. Introduction

A problem of current interest concerns the exposure of biological samples to fast intense electromagnetic pulses, for the purpose of studying cell processes and killing cancer cells [14]. The problem then becomes how to do this. One can focus a fast pulse (100 ps or so) in the near field using a prolate spheroidal reflector [10]. Even larger fields can be achieved by a system involving direct contact by guiding conductors.

It is desirable to move the direct-contact apporach into the 100 ps regime. This requires careful consideration of the test cell for holding a simple of the 1 cm or so size, and exposing the sample to MV/m fields.

2. Overall Geometry

Figure 2.1 shows the geometry of the test cell. A cylindrical sample of length ℓ and radius α is to be exposed to the electromagnetic pulse. A pulse is launched from the opposite end of the fixture onto a coaxial transmission line of inner radius a and outer radius b, with characteristic impedance

$$\begin{aligned} Z_c &= Z_0 \, f_g \\ Z_0 &= \left[\frac{\mu_0}{\varepsilon_0}\right]^{1/2} = \text{wave impedance of free space } (\simeq 376.7 \ \Omega) \qquad (2.1) \\ f_g &= \frac{1}{2\pi} \ell n\left(\frac{b}{a}\right) \quad \text{(geometric factor)} \end{aligned}$$

Here we have assumed a pressurized gas dielectric (such as hydrogen), with permittivity, ε_0, and permeability, μ_0, approximating the constitutive parameters of free space. This is particularly appropriate if repetitive pulsing is to be used.

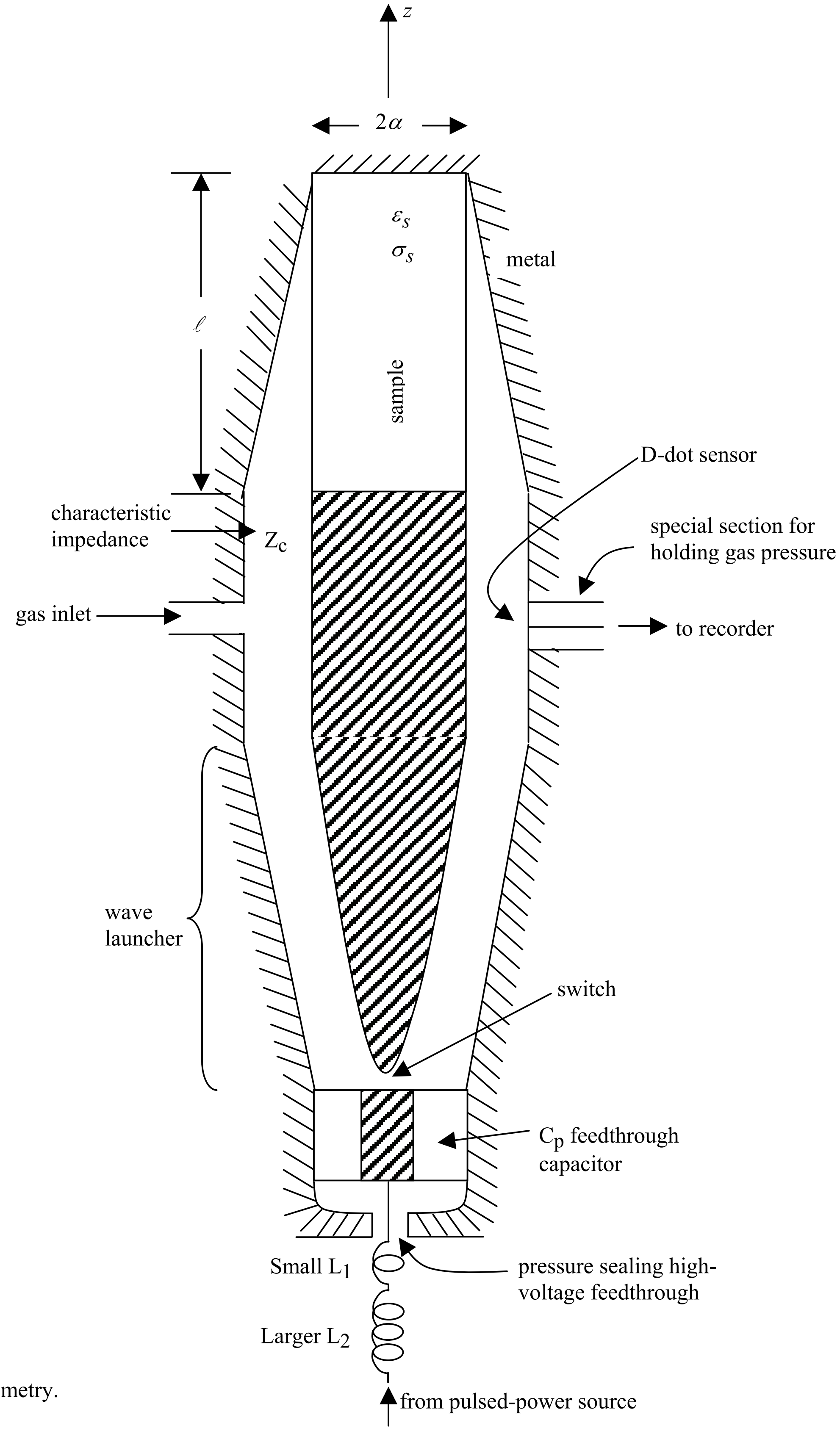

Fig. 2.1 Test-Cell Geometry.

3. Matching Into Sample

For present purposes let our sample be characterized by a saline solution with [13]

$$\begin{aligned} \varepsilon_r &= \frac{\varepsilon_s}{\varepsilon_0} = 80 \quad \text{(relative dielectric constant)} \\ \sigma_s &= 0.3\,\text{S/m} \quad \text{(conductivity)} \end{aligned} \tag{3.1}$$

Various biological cells may be present in this solution. With length ℓ and radius α the sample has

$$\begin{aligned} R_s &= \frac{\ell}{\pi a^2 \sigma_s} \quad \text{(resistance)} \\ C_s &= \varepsilon_s \frac{\pi a^2}{\ell} \quad \text{(capacitance)} \\ \tau \equiv R_s C_s &= \frac{\varepsilon_s}{\sigma_s} \quad \text{relaxation time)} \end{aligned} \tag{3.2}$$

For the assumed parameters

$$\tau \simeq 2.36\,\text{ns} \tag{3.3}$$

So here we can see that we are looking for biological samples with pulse widths less than the sample relaxation time. Note that if σ_s is increased to say 4 S/m (sea water) the relaxation time is reduced to about 177 ps.

Matching Z_c to R_s we have

$$\begin{aligned} Z_c &= R_s = \frac{\ell}{\pi a^2 \sigma_s} \\ \ell &= 2\,cm \quad \text{(assumed length)} \\ Z_c &= 50\,\Omega \quad \text{(assumed impedance)} \\ a &= \left[\frac{\ell}{\pi \sigma_s Z_c}\right]^{1/2} \simeq 2.1\,\text{cm} \end{aligned} \tag{3.4}$$

For sea water this would reduce to about 5.6 mm.

A $50\,\Omega$ coax would have outer radius of

$$\begin{aligned} b &= a\, e^{2\pi f_g} \\ f_g &= \frac{Z_c}{Z_0} \simeq \frac{50}{376.7} \simeq 0.133 \\ b &\simeq 4.84\text{ cm} \end{aligned} \tag{3.5}$$

For the sea-water case, this is approximately 1.29 cm. As indicated in Fig. 2.1, the outer conductor slopes from b to a in going along the sample. As discussed in [8] the characteristic impedance of the coax should taper from its full value to zero at the end of the sample with $dZ_c / dz = R'$ (resistance per unit length of the "terminator"). This makes an angle with respect to the sample of

$$\psi = \arctan\left(\frac{b-a}{\ell}\right) \simeq 54^\circ \tag{3.6}$$

a fairly steep angle. For sea water, this reduces to about 20°.

There is also a capacitive term due to ε_s. One can match into this using the Brewster angle as indicated in Fig. 3.1. This angle is given by

$$\psi_B = \arctan\left(\varepsilon_r^{-1/2}\right) \simeq 6.4^\circ \tag{3.7}$$

which is much smaller than the previously considered values of ψ. This in turn implies

$$\begin{aligned} b-a &= \ell \tan\left(\psi_B\right) \simeq 2.24\text{ mm} \\ Z_c &\simeq Z_w \frac{b-a}{\pi\left[b+a\right]} \simeq 6.3\,\Omega \end{aligned} \tag{3.8}$$

This is a very small impedance, creating its own difficulties.

At times less than the relaxation time we can think of the sample as capacitive. However, this has to be tempered by the short wavelength in water. While 100 ps corresponds to 3 cm in air (covering the sample length), it corresponds to about 3.4 mm in water, less than the previously considered sample radius. Basically we have an approximate cylindrically imploding (focusing in time domain) wave. This will increase the field on axis which could be useful, but the field will not be uniform throughout the sample.

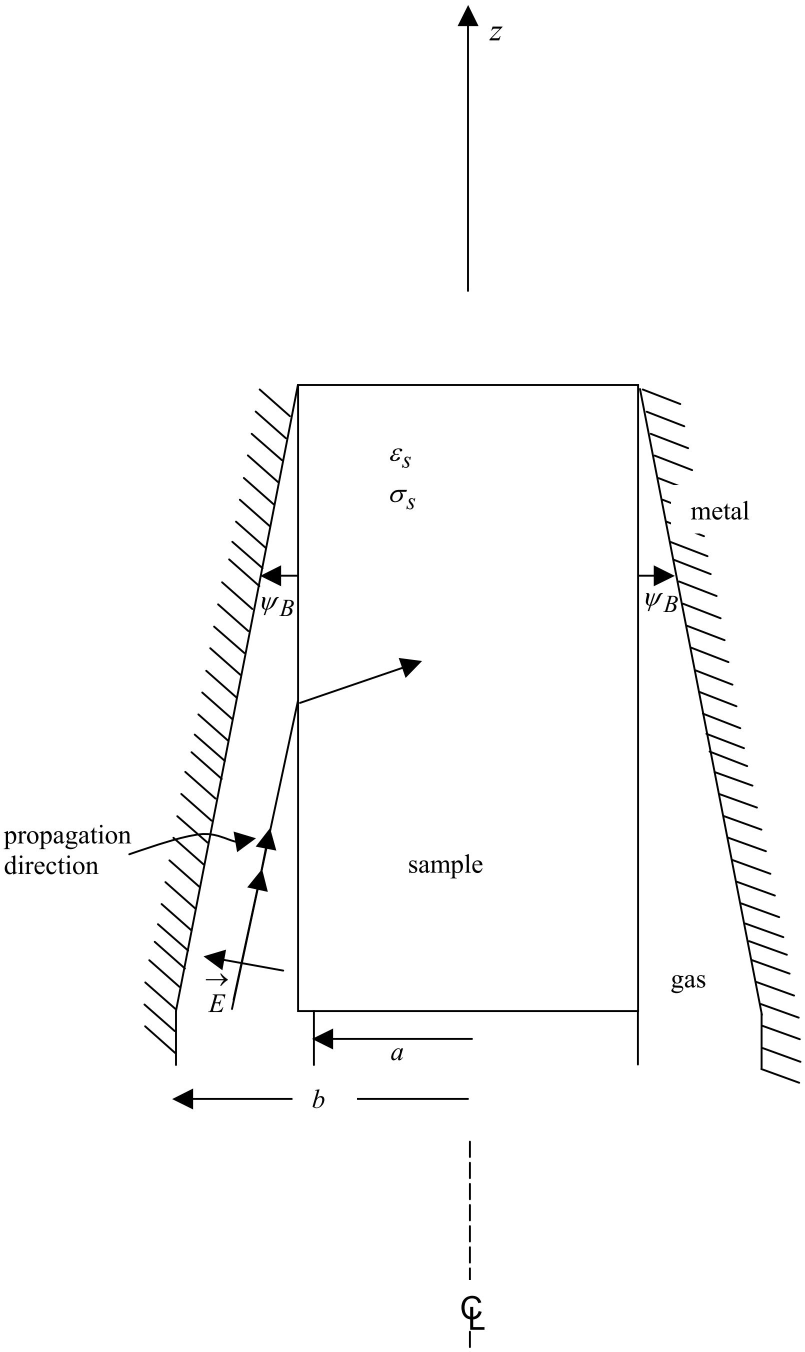

Fig. 3.1 Brewster-Angle Matching of Wave Into Test Sample

So let us consider some other possibilities. Suppose we set $a \simeq 2\,\mathrm{mm}$ to obtain a more uniform field. Then we have

$$\begin{aligned} \ell &= 2\,\mathrm{cm}\ ,\ a = 2\ \mathrm{mm} \\ R_s &= 5.3\ \mathrm{k}\Omega \\ C_s &\simeq 0.45\ pF \end{aligned} \qquad (3.9$$

For times less than τ (3.3) the sample looks capacitive to a 50 Ω source, giving a negative reflection, lowering the voltage across the sample. Of course *a* can be reduced to less than 1 mm, and Z_c can be lowered below 50 Ω so that

$$\begin{aligned} Z_c C_s &< 100\ ps\ \text{ or so} \\ Z_c &\simeq 20\,\Omega\ \text{ (say)} \\ C_s &< 5\ pF \end{aligned} \qquad (3.10)$$

Using the (3.9) capacitance with 20 Ω for Z_c gives

$$Z_c C_s \simeq 9\ ps \qquad (3.11)$$

However, the sample resistance is now 5.3 $\mathrm{k}\Omega$. This is large compared to Z_c indicating an approximately +1 reflection, thereby almost doubling the voltage on the sample (a possible advantage). To accommodate the small sample radius one could modify the sample configuration as in Fig. 3.2. There is also the problem of the subsequent reflection of this pulse from the source end.

As we can see there are various competing considereations for the design of the test cell. This will partly depend on the problems associated with the sample holder, including placing it in the high-pressure test cell. The example given in the previous paragraph (thin sample) appears best from an electromagnetic point of view, but there are other considerations.

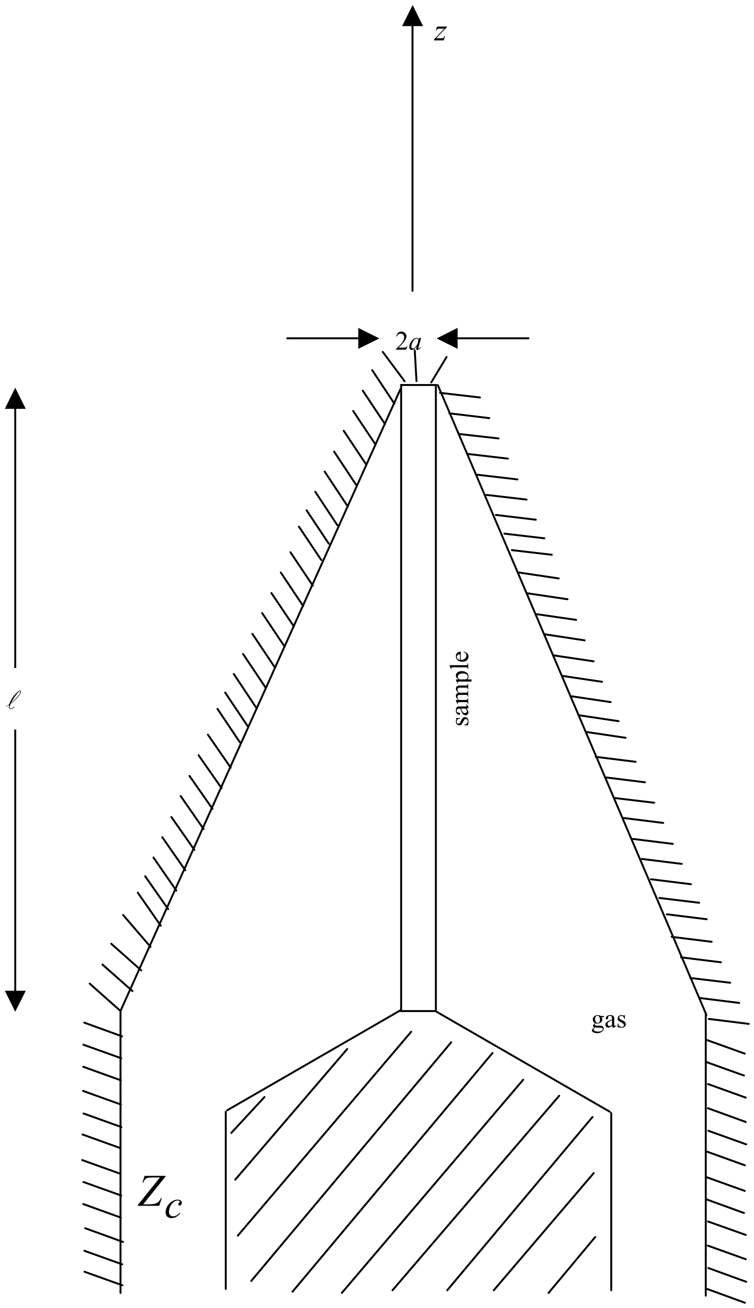

Fig. 3.2 Test-Sample Configuration for Small Sample Radius.

4. Switching Pulse Into Holder

After we have decided on an appropriate Z_c we come to the problem of launching a 100 ps (or so) pulse on this transmission line from the end opposite to the sample (as in Fig. 2.1). There are various details to consider. First there is the switch inductance. As discussed in [12], for a 1 mm gap (typical) we have

$$\begin{aligned} \mathrm{L}_s &\simeq 1\ nH \\ Z_c &\simeq 20\,\Omega \quad \text{(say)} \\ \frac{\mathrm{L}_s}{Z_c} &\simeq 50\ \text{ps} \end{aligned} \tag{4.1}$$

Giving a rise time of approximately 100 ps, comparable to the desired pulse width. It should be noted that rise times of about 100 ps have been achieved at voltages of over 100 kV [7, 9]. However, the impedances driven were 100 Ω or so. This is a challenging problem.

The next problem is to get the wave from the switch launched on the coaxial transmission line of impedance Z_c. As illustrated in Fig. 4.1, this can be accomplished by a biconical section, also of characteristic impedance Z_c [2]. If this is characterized by two polar angles ψ_1 and ψ_2 we have

$$\begin{aligned} Z_c &= Z_w f_g \\ f_g &= \frac{1}{2\pi}\ell n\left(\frac{\cot\left(\frac{\psi_1}{2}\right)}{\cot\left(\frac{\psi_2}{2}\right)}\right) \end{aligned} \tag{4.2}$$

Besides matching impedances we need to match transit times for the various ray paths to the cylindrical section [15]. While we cannot do this perfectly without inserting a lens, we can make a good approximation by making ψ_1 and ψ_2 sufficiently small [1].

For the pulse source let there be a feedthrough (very low inductance) capacitor C_p. For a short pulse this is quite small with

$$\begin{aligned} Z_c\, C_p &\simeq 100\ \text{ps (or so)} \\ C_p &\simeq 5\ \text{pF} \end{aligned} \tag{4.3}$$

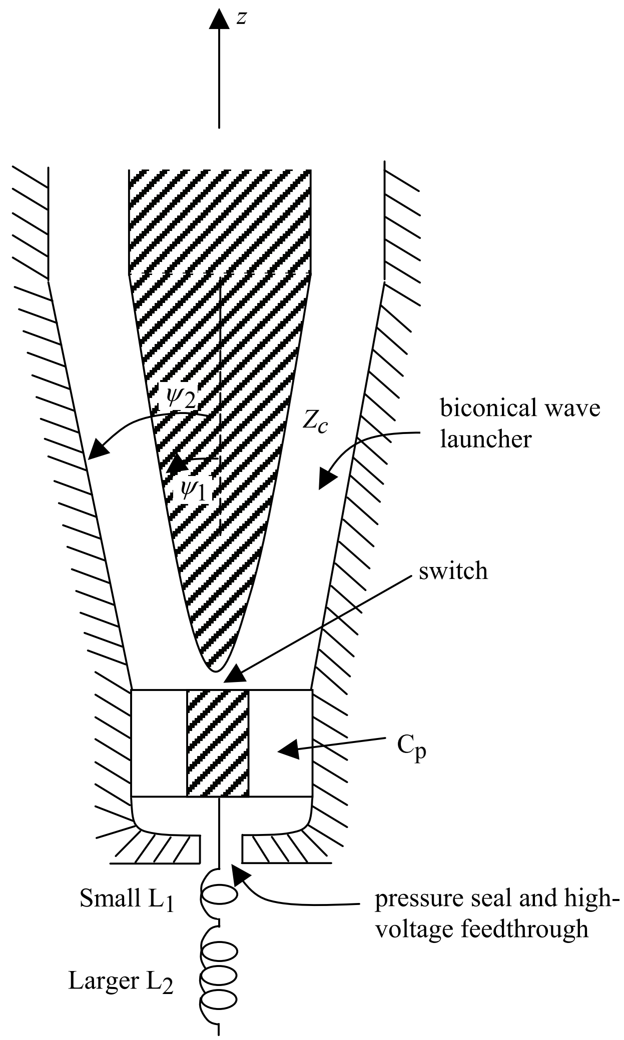

Fig. 4.1 Launching Wave Toward Test Sample

Perhaps C_p should be increased to allow the full charge voltage to be launched toward the test sample. Now C_p has to be charged up to the self-break voltage of the switch. This might come from a Marx generator, resonant transformer, or whatever, which (relatively) slowly charges C_p. If we wish to minimize the propagation of the fast pulse back toward the high-voltage source, some inductance might be included in the charging line near C_p. This can include a small inductance, L_1 (for good high-frequency performance), followed by one or more inductors (larger) of inductance, L_2. The radiation from these coils can be minimized through special designs which remove the magnetic dipole moment [5, 6].

5. Diagnostics

We need some way of measuring the fast, high-amplitude pulse exciting the sample. Figure 2.1 shows one method where a D-dot sensor is placed in the outer wall of the coax. This might look like a small-diameter (to reduce forces from the pressurized gas) coax with the center conductor (and dielectric) cut flush wish the test-chamber outer conductor. One can make some estimates of the sensitivity [3, 4]. One can also calibrate the constructed version. If the sensitivity is too large the center conductor can be recessed.

Another technique involves taking a high-voltage signal from the center conductor and reducing it, such as by some kind of fast, accurate voltage divider [11]. At the same time we don't want to significantly load the test-chamber voltage with this device.

One may also want some diagnostics of what is happening in the test sample. On a short-time (or even real-time) basis (before the test sample is removed from the chamber), one might install an optical viewing port with appropriate attention to the high gas pressure.

6. Concluding Remarks

So now we have some feeling for the electromagnetic parameters of such a fast-pulse test cell. As we can see there are various tradeoffs to be made. There will likely be some adjustments needed to be made in the design. So an early version might include some possibility to vary some of the parameters.

The mechanical design also poses significant problems associated with the high pressure. The sample must be inserted and removed, and have an appropriate outer barrier between the gas and the sample. The ends of the sample, of course, make electrical contact with the test fixture. We also need to be able to adjust the pressure and the switch-gap spacing.

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