# Tuner Topics

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*Understanding the dynamics of your matching network can ensure that you have an efficient, dependable process design and a well-integrated blueprint for long-term processing success.*

Although simple in component design, tuners can create or solve significant problems in plasma processes. Placement and connections dramatically affect RF power supply performance, process efficiencies, and safety. In fact, improperly installed tuners are a frequent cause of system damage and downtime.

One common misconception is that the RF power readings at the tuner should correspond to the RF power readings at the generator. This is rarely the case—readings are rarely within 10%. When there is a disparity between the calibration of the tuner and the generator, many items contribute varying amounts of error. The following are just a few:

- *The insertion loss of the transmission line between tuner and generator*
- *Differences between the directional couplers of generator and tuner, particularly if they are of different manufacture*
- *Tracking and linearity errors between the detectors attached to the directional couplers*
- *Changes in the electrical length of the transmission line with temperature (typically 0.05 electrical degrees per 45° per 10°C)*
- *Change in cable attenuation with time (typically 0.1 dB per 100′ per 60 days at high humidity)*
- *Changes with time in the instrumentation following the detectors*
- *Reading accuracy of analog meters (typically 3% for meters without mirrored scale)*

This discussion will examine the design implications of these factors, typical tuner configurations, the tuner-chamber relationship and calibration, common system errors, and adjustments for optimal performance.

## Description

A tuner is an electromechanical apparatus that transforms an electrical load impedance of R ±jX at the chamber to a constant R at the output of the generator. The input value of R conforms to the characteristic impedance of coaxial transmission lines (usually 50 Ω or 75 Ω). The tuner configuration is shown as an "L" network, composed of two variable reactances of opposite sign (Figure 1).

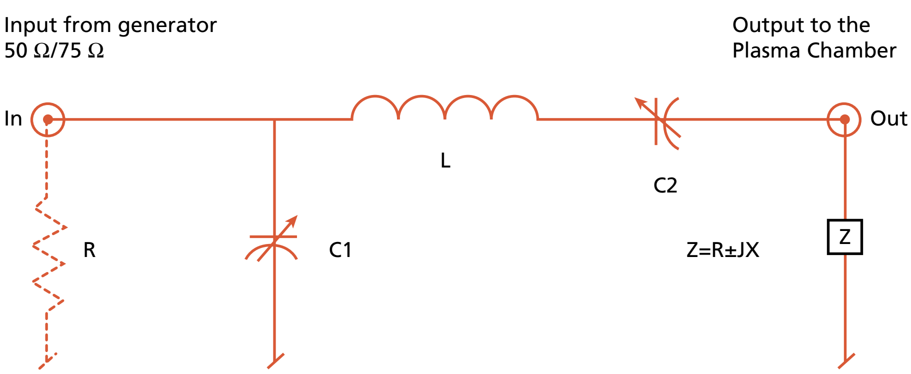


Figure 1. A simple matching network

The fixed inductor, L, is connected in series with two variable capacitors. This allows you to vary L by adding or subtracting an opposite reactance. This configuration is a more practical and trouble-free arrangement than a tapped, or sliding, contact inductor.

The components that compose the basic arrangement of a manually adjusted tuner include the L network with a compatible coaxial RF fitting at the input; stout, well-insulated output terminals (usually threaded); and control knobs and shafts for C1 and C2 (well-insulated for C2), mounted together in a suitable aluminum enclosure.

For greater flexibility, servo drives for C1 and C2 may be added. The servo amplifiers are driven by analog signals derived from phase and magnitude detectors. This configuration, too, is contained in a suitable enclosure with appropriate connectors, manual switches for presetting the tuning elements (auto/manual, forward/reverse), capacitor position indicators, and appropriate forward/reverse power indicators.

Tuners vary considerably from one manufacturer to another, and the more spartan equipment probably will not include RF power indicators or the position of reactances.

## Installation

Proper installation of the tuner is vital to the successful operation of the plasma chamber. A poorly installed tuner can undermine power efficiency, cause over-heating of tuner components and connections, disable tuner functions, and cause stray RF fields (which can get into the instrumentation) and other serious problems.

Figure 2 illustrates an optimal tuner-to-chamber installation. Note the four factors highlighted below.

### Placement

The tuner is bolted to the chamber directly over the vacuum feedthrough, minimizing leads to the electrodes.

### Lead Surface Area

The leads must be appropriate for the power level and frequency to be handled.
Use silver-plated copper strap (not braid), 3" minimum width, 12" maximum length. Separately insulated straps are used for the "hot" lead and the ground leads. This minimizes lead inductance and $I^2R$ losses.

### Connections

Bolted connections equipped with silver-plated brass washers keep contact resistance to a minimum.

### Output Cable Attenuation

Coaxial cable can be used successfully from the tuner output to the plasma chamber, after taking certain precautions.

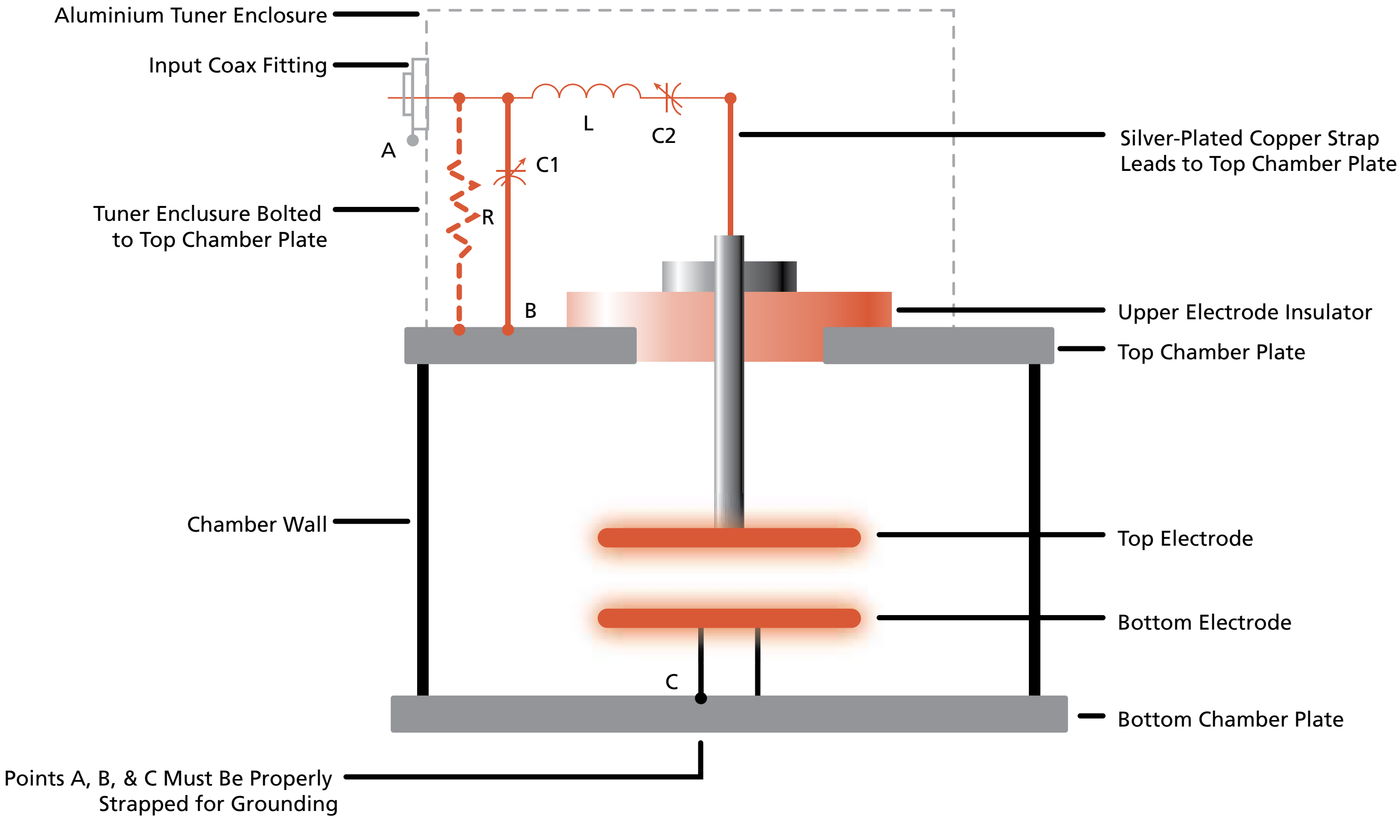


Figure 2. Tuner-to-chamber installation (tuner is mounted directly to the top plate of the chamber)

## Coaxial Cable Attenuation

If you must use coaxial cable, be aware that serious problems can occur if inadequate cable surface area is provided or if lead lengths are not minimized. In fact, this is the most common cause of load-matching problems.

For example, the attenuation of RG-8/U(RG-393) coaxial cable is 0.7 dB per hundred feet at 13.56 MHz. This is the attenuation of the cable when it terminates into a 50 Ω resistive load. The attenuation will increase when the line terminates into a load other than 50 Ω. The increased attenuation is given by:

$$Aa=A\left[\frac{\rho^2+1}{2\rho}\right]$$

Where:
A=Initial attenuation
Aa=Final corrected value of attenuation
ρ=VSWR

A plasma load of 5 Ω using a 6' length of RG-8/U cable has a VSWR of 10 to 1 and initial and final values of attenuation equal to:

$$A=0.007\text{ dB}\times 6'=0.042\text{ dB}$$

$$Aa=0.042\text{ dB}\left[\frac{101}{20}\right]=0.212\text{ dB}$$

If the input power were 1000 W to the matched line, the power loss would be:

$$\text{dB}=10\log\frac{Po}{Pi}=-0.042;\text{ then }\log\frac{Po}{Pi}=-0.0042$$

$$\frac{Po}{Pi}=10^{-0.0042}=0.9904;\ Po=990.4$$

$$\text{Power loss}=Pi-Po=9.6\text{ W}$$

For the same input and a VSWR of 10 to 1, the attenuation is now 0.212 dB, and power loss is:

$$\text{dB}=10\log\frac{Po}{Pi}=-0.212;\text{ then }\log\frac{Po}{Pi}=-0.0212$$

$$\frac{Po}{Pi}=10^{-0.0212}=0.952;\ Po=952$$

$$\text{Power loss}=Pi-Po=48\text{ W}$$

These power losses can cause unpredictable changes in system power calibration and clearly illustrate the problems caused by the wrong cable.

Now, consider type RG-220/U. Its loss per hundred feet is 0.17 dB, about one-fourth the loss of RG-8/U. A second alternative is to use two pieces of cable in parallel. This gives a dual advantage: 1) the power loss will be halved, and 2) since the cable $Z_o$ will be 25 Ω instead of 50 Ω, the loss due to VSWR also will be halved.

## Tuner-Chamber Relationships

The only purpose of the tuner is to transform the chamber impedance of R ±jX into a constant 50 Ω or 75 Ω of pure resistance. This allows the generator and transmission line to operate at maximum efficiency. Remember that tuner calibration need not precisely coincide with generator calibration. The tuner power indicators simply are there to display whether the tuner is "at tune" (minimum reflected power) or not.

The chamber impedance before ionization is capacitive. The value of capacity is readily calculated by measuring the area and spacing of the electrodes and referring to the dielectric constant of the gas at chamber pressure. The reactance then can be calculated at the frequency in use.

The imaginary portion of the chamber impedance is expressed as:

$$XC = \frac{1}{2\pi f C}$$

Since the gas is not ionized, it has high resistivity and makes part of the chamber impedance under this condition very high. The chamber voltage, E, will be equal to $\sqrt{P(Xc)}$, where P equals forward power of the generator at the chamber, not at the generator. (This is due to the additional line loss caused by the mismatched condition. See *Coaxial Cable Attenuation* on page 4.)

When power is applied, the tuner servos will run, attempting to match, or transform, the capacitive reactance to a real (resistive) input impedance. The tuner, however, cannot transform a pure reactance into a resistance. Therefore, it will run or "search" until the chamber ignites, or the tuner runs into the end of its range.

Depending upon the design of the tuner, it will either: 1) reverse its direction of tuning or 2) remain against its limit switches or stops. Condition 1 is preferred.

When the chamber won't light, there may be a very elementary problem: the voltage at the plates is less than the striking voltage of the gas type in use.

The solution is equally elementary. Calculate the chamber impedance (reactance). Measure the forward power at the chamber. Calculate the chamber voltage, E= $\sqrt{P(Xc)}$. Refer to a table of striking voltage versus gas type and pressure. Then, you will be ready to take corrective action as necessary, i.e., increase gas pressure, increase power, reduce losses, etc.

## Impedance of the Plasma Chamber

The impedance of the plasma chamber will vary widely depending upon plate area, plate spacing, gas type and pressure, temperature, and other parameters. Typically, the impedance consists of resistance and capacitive reactance, with R values from a few ohms to tens of ohms, and Xc from tens of ohms to hundreds of ohms.

The RF current into the plasma chamber with low Z values and power in the kilowatt range can reach sizable values. Since the RF skin effect at 13.56 MHz is about 0.7 mil, adequate surface area should be provided by using multiple strap leads.

## Transmission Line Transformation of Chamber Impedances

Consider the equation below, which reveals that the input impedance to a transmission line is a function of its length, its characteristic impedance, and the impedance of the load when the load is not a pure resistance equal to the characteristic impedance.

$$ZIN = \left[ \frac{ZR + jZO \tan \beta L}{ZO + jZR \tan \beta L} \right]$$

Where:

ZIN=Input impedance

ZO=Characteristic impedance of the line

ZR=Load impedance

βL=Line length in electrical degrees

i.e., $\beta L = \frac{2\pi}{\lambda}$; where λ is the wavelength in the line, including its velocity factor, or the line length in degrees per meter of length

tanβL=The tangent of βL

These equations show that impedance presented to the tuner will be different from chamber impedance and can be of opposite reactance as compared to the actual chamber reactance (usually capacitive). The end result is that the tuner may not be able to transform the new value of Z into a flat 50 Ω. Thus, the value(s) of L and C in the tuner will have to be modified.

If you must use coaxial cable, keep the length to 3' or less so that tanβL will not greatly modify the impedance from chamber to tuner. Using parallel connected coaxial cables, such as two 50 Ω pieces, will reduce ZO in the equation to 25 Ω, further reducing the excursion of ZIN.

## Chamber Calibration

The plasma chamber is a reactive electrical load. As such, the chamber can produce electrical and sometimes visible oscillations. These oscillations can interfere with the "normal" operation of the chamber, the generator, the tuner, and the instrumentation. There are several methods that can be employed to detect the presence of chamber oscillations. The best method is to use a dual-directional coupler and a spectrum analyzer (Figure 3).

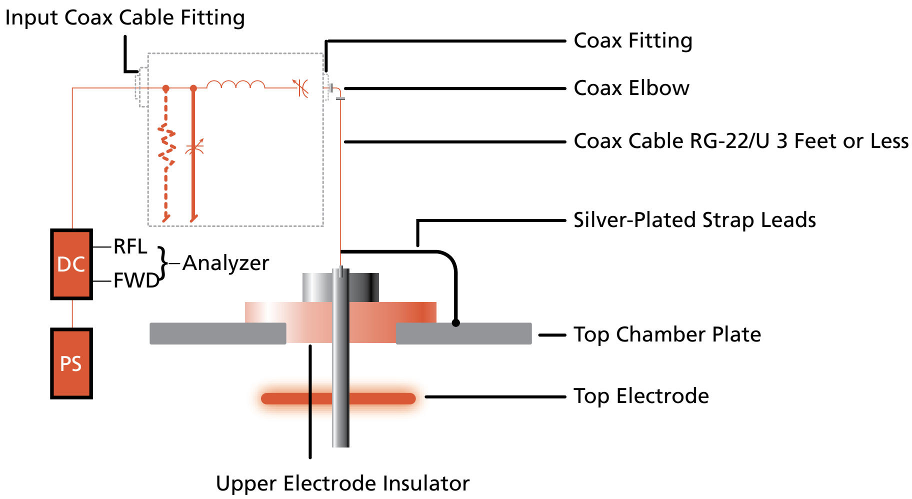


Figure 3. Chamber installation (using coaxial cable from tuner output to chamber plates) and calibration

The coupling ratio and directivity of both ports of the coupler must be known or calibrated. Insert the coupler in the transmission line between the generator and the tuner. Observe the analyzer display with the analyzer adjusted to display the fundamental generator frequency to a full raster. Set the generator in the cw mode. Now record the frequency and amplitude of all signals observed over the frequency scan bandwidth of interest.

Repeat the same steps with the analyzer connected to the reflected port. An oscilloscopic camera can be of great assistance in these measurements. Now sort the displayed data as follows:

1. *Identify any frequency that is an exact multiple of the fundamental and label it by its harmonic number.*
2. *Identify and label any frequency that is not an exact multiple of the fundamental.*
3. *Identify and label any frequency that lies close to the fundamental, such as 1 kHz, 10 kHz, etc.*
4. *Operate the generator into a dummy load, and scan the forward port of the coupler. Identify and label all visible signals.*
5. *Compare all power signals obtained in step 4 with 1, 2, and 3 forward and reflected power ratings. Remove all signals that match from the data bank.*
6. *Any signals in steps 2 or 3 that do not match in frequency with step 4 are now suspected of being chamber generated. To confirm this, measure the amplitude of the suspected signal at the forward and reflected ports of the coupler. A chamber-generated signal will be of higher amplitude on the reflected port as compared to the forward port by the directivity of the coupler at that frequency.*

## Operator Troubleshooting

Some operational problems have simple solutions. If your system exhibits any of the specific symptoms below, try the actions recommended here.

| Symptom | Action |
|---|---|
| Power won't come on. | Check fuses, RF grounds, and input power connection. |
| System won't reduce reflected power below 10% of forward power. | Check output power connection and system grounds. Load impedance may be beyond design limits. Check the tuner. |
| System exhibits sharp over-shoots and oscillations around minimum reflected power. | Check system grounds and RF output connections. |
| The matching network cannot be tuned in one direction. | Larger or smaller series inductance may be required. |
| Cable or connectors between tuner and chamber are hot. | Check RF grounds. Lower the impedance between the tuner and the chamber. Move tuner closer. Use leads and conductors with a greater surface area or types that can better handle the power level and frequency. |

To view AE®'s portfolio of matching networks and RF power supplies, visit:
*www.advanced-energy.com/en/RF.html*

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