Limitations of a Load Pull System

General Rule: The Critical Sections in a Load Pull measurement setup are the sections between the RF Probe of the tuners and the DUT. The Reflection and Insertion Loss of these sections has to be minimized by all means and expenses.

There are also a number of limitations, some due to the nature of the tuners and the setup and some due to the software:

Reflection Factor (Impedance):
Accuracy Limitations
Power Handling Limitations
Speed Limitations
Parasitic Oscillations
Transistor Breakdown

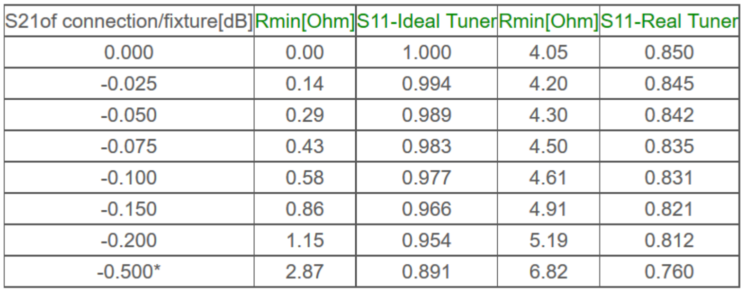
Reflection Factor (Impedance) Limitations:

Tuner Reference Plane: Electromechanical tuners may generate repeatable reflection factors up to 0.95 at different frequencies before creating a short circuit. For electronic tuners this value is around 0.8. Over a wide frequency range one should expect reflection factors around 0.85-0.9 (VSWR~15:1 to 20:1). Keeping in mind that a mechanical tuner can always create a short circuit (Gamma=1) the real question becomes: How accurate can one measure at a high reflection factor? This depends on two factors: 1) The calibration accuracy of the network analyzer used and 2) the mechanical accuracy of the tuners.

NEW: Since the introduction of the Prematching Tuner Concept by Focus Microwaves in May 1999, we have been able to synthesize reflection factors of up to 0.99 with very high accuracy (40dB or better). This is not against the basic rules of accurate calibration, outlined above; rather it is the way Prematching Tuners work and are calibrated that allows this apparent “contradiction” to happen.

DUT Reference Plane: Most limitations do not come from the tuners used (even though high reflection at the tuner port helps). They come from using lossy connections (cables, adapters, test fixture insertion loss, etc...) between the DUT and the tuners. This becomes even worse when

Diplexers or Triplexers are used for certain types of harmonic load pull setups (Triplexers have typical insertion loss of more than 1dB). The following table shows the minimum resistance tunable by an "Ideal" Tuner (with Reflection factor=1) and by a "typical" Real Tuner (Reflection factor=0.85/ SWR=12.5:1) as a function of the insertion loss of this connection (S21):



S21of connection/fixture[dB]	Rmin[Ohm]	S11-Ideal Tuner	Rmin[Ohm]	S11-Real Tuner
0.000	0.00	1.000	4.05	0.850
-0.025	0.14	0.994	4.20	0.845
-0.050	0.29	0.989	4.30	0.842
-0.075	0.43	0.983	4.50	0.835
-0.100	0.58	0.977	4.61	0.831
-0.150	0.86	0.966	4.91	0.821
-0.200	1.15	0.954	5.19	0.812
-0.500*	2.87	0.891	6.82	0.760

* Higher values are not considered here as a state of the art solution. However Triplexers in some harmonic load pull setups have almost 1dB loss and the measurement may be worthless. A practical alternative is Active Injection: it is an "open loop" technique, it requires a second, synchronized source and avoids notorious spurious oscillations of "closed loop" techniques. A pre-matching passive tuner leads to "hybrid" systems and reduces the requirement of very high power injecting amplifiers.

Accuracy Limitations

Load Pull measurements are critical with regard to tuning accuracy. Please notice, we use the term "tuning" accuracy, not "tuner" accuracy, as it is not the same. Tuning accuracy includes all sources of error:

Resolution problems: Not being able to tune to a very specific impedance. In load pull we have to present the DUT exactly its matching impedance, as interpolations of the nonlinear behavior of the transistors are risky and not established theoretically. So, either we use very lengthy calibration routines including thousands of points (Maury) or interpolation algorithms with acceptable interpolation capability (Focus). Electronic tuners (ATN) are limited to a maximum of ~1000 impedance points with no further increase possible.

VNA calibration problems: Not using TRL, poor and worn out cables and connectors, use of 3 detector network analyzers like 8753..

Tuner Calibration problems: In general absolute calibration accuracy degrades rapidly at VSWR > 15:1. Possible errors may exceed 1dB in calculated tuner loss; Tuner Loss=(1-|S11|2)/|S21|2

uner mechanical Repeatability problems. Focus responsibility is the quality of the tuners which

enable overall tuning accuracy of 40dB or better (see PN-50 in Literature section), but we often observe the other causes for measurement error to far exceed possible tuner inaccuracy issues.
Power Handling Limitations

Two factors limit the handling power of the load pull system (except of the specified power for cables, adapters, isolators, 50 Ohm loads, attenuators and power detectors, which are beyond the topic of this note):

The Tuner Connectors limit the RF power due to thermal breakdown: Small dc resistances heat up at high current densities and create a runoff thermal phenomenon at the point of contact between the tuner port facing the DUT output and the test fixture. This is the most critical point in the setup. Using APC-7 connectors, or worn our SMA connectors worsen the situation, because the galvanic contact between the central pins is not good enough. Using N or 7/16 connectors increases power handling by a factor of 3 to 5. We found APC-7 connectors able to handle 30 Watts at VSWR=10:1 safely, N-connectors around 70 Watts and 7/16 connectors beyond 100 Watts. For those "high power" connectors both the central pin contact is far better and their metallic mass big enough to distribute heat. APC-7 connectors can be improved if we insert a tight fitting copper pin between the central conductors at the point of contact. However good fitting may be a delicate matter to adjust.

Corona Discharge in the Tuner Transmission Linesbetween the central conductor and the RF probe at very high VSWR and power. This happens in general when edge effects are predominant on the probes or inhomogenities in the central conductor. This phenomenon is observed in older tuner models more than newer ones, probably because of worn out probe isolation, marks or scratches. At the beginning this effect is not destructive and the tuner remains operational. If repeated the probe isolation may be damaged as well as the central conductors. To avoid this effect the tuners have to be operated at lower VSWR (which is recommended also for measurement accuracy reasons). The final high VSWR can be obtained using Transformers. In on-wafer tests transformers are not possible, but then the RF power is not very high either. Because the reflection in a slide screw tuner is created by the physical proximity of the RF probe and the central conductor of the airline (capacitive effect) high electric fields can be generated. As an example: for 50 W CW power reflected in a tuner at S11=0.95 (SWR=39:1) the peak electric field under the probe, which is about 0.1mm away from the central conductor, reaches over 44kV/cm. At S11=0.92 (SWR=24:1) the maximum field is around 35kV/cm. These values are very close to the electrical breakdown field in air (vacuum). A dielectric coating under the probes may prevent a corona discharge for some time but minor surface imperfections and scratches will deteriorate the performance of the tuner n regard to high field corona discharge.
For the above two reasons it is practically impossible to accurately specify the maximum power handling capability of slide screw tuners, since a most important operation condition, << the ac tual distance of the RF probe to the central conductor >> , is practically impossible to control and

report accurately in real operation.

Speed Limitations

Measurement Speed is limited by two factors

Tuning Speed: This is the time needed for the tuner to travel from one position to the next. At a rotation speed of the tuner motors of 500 steps/second and a step size of 25.4 micrometers/step we obtain a tuning phase speed of 30 degrees/second at 1 GHz (or 60 degrees/second at 2 GHz etc..). In vertical direction it takes about 2-3 seconds to tune from Gamma=0.1 to Gamma=0.9. Tuning speed remains roughly constant over the frequency ranges, since at higher frequencies we use higher resolution tuners. The vertical tuning speed is also not changing much (up to a maximum of 2:1 for millimeter wave tuners).

Instrument Reading Speed:This quantity varies enormously between instruments and depends also on the algorithms and GPIB cards and drivers used. We observe the largest influence to come from the particular instruments. Especially older power meters (HP-438A) are very slow, whereas newer models (HP-4142 or Anritsu ML-24XXA and Boonton 4400) are much faster, especially when they use Detector instead of Bolometer heads. Specific measurement routines like ACPR and IMD are also long and can cause delays exceeding the tuner caused delays by a factor of 2:1 to 5:1. For instance tuner movement is typically 200 to 300ms at 2GHz and instrument reading 200ms to over 1 second with fast instruments measuring a set of 5 to 7 parameters (Pin, Pout, PAE (=Id,Vd,Ig,Vg) as an example).

Parasitic Oscillations

Parasitic oscillations are annoying because they falsify the measurement results, change the shape of contours and are, in general, discovered after the end of the measurements. In many cases they may lead to a destruction of the transistor. The cause of parasitic oscillations may lay in the tuners, the test fixture or the setup.

The tuners may create impedances within the instability range of the DUT both on source and load side at unpredictable frequencies. In general if the tuners have a “low pass” behavior, as Focus tuners do, parasitic oscillations at lower frequencies are not generated. At higher frequencies the gain of the transistors generally drops, and so does the oscillation tendency.

The Test Fixture may cause parasitic oscillations if it carries low impedance transformer sections and even more if it carries bias networks. Bias networks in the fixture are sometimes required for high current, special frequency traps and DC protection from eventual shorts in the tuners.

The setup components may also cause parasitic oscillations, especially Isolators (Circulators): It is

often forgotten that Isolators normally create high reflection outside their pass band. This may cause parasitic oscillations, if the transistors are potentially unstable at these (in particular lower) frequencies. In this case only broad band 3dB attenuators inserted between the isolators and the DUT may solve the problem. This will, on the other hand, increase the requirement for input power. We choose 3dB because it does not limit the input power too much, still guaranteeing an acceptable level of low reflection (=6dB return loss). Bad cables, Bias Tees and adapters may also create enough reflection to cause un-controllable oscillations.
How to Deal with Parasitic Oscillations?

Improve the Setup (low reflection components, damping resistors in the gate...)
Study the transistor, tune manually and observe the spectrum analyzer, plot stability circles and avoid instability areas during load pull (section measurements).
Use specific routines, which detect oscillations using a spectrum analyzer and mark the bad points in a file to avoid them during the test. Such routines are part of WinPower.
Eliminate bad points during graphic processing by employing “filters”. Such filters are part of Focus’ Contouring Software “WinGraph”.

Transistor Breakdown

Transistor breakdown may happen if the Gate-Drain (or Base-Collector) voltage exceeds the breakdown voltage of the device. This may happen even at medium input power if the source impedance is such as to create a high voltage at the input terminals. In order to compute the actual peak voltage at the input terminals of the device not only the injected power and source impedance are required but also the device large signal input impedance. Only approximate calculations are possible. A formula has been derived and used in previous versions of the CCMT load pull software, but it revealed impractical to employ, due to extra required information to be entered by the user. The formula that can be used to calculate the maximum power injected into the DUT before breakdown occurs is:

Other, more practical methods, have been developed meanwhile and are part of the WinPower software:

Reduce the Source Power by a user defined amount (typically 20dB) during tuner movement. This method is called “Power Sampling”.
Return to 50 Ohms between tuned points (withdraw the RF probe before moving horizontally). This method is called “Probe Sampling”.

This section is being regularly updated using the latest knowledge in the art.