generating knowledge

PRECISION IN PROCESSING

TRUMPF Hüttinger generators deliver output power with 0.35% accuracy over the calibration interval – process-to-process deviation is typically less than 0.1%

Abstract

Moore's law requires enduring improvements in semiconductor manufacturing processes to ensure a continuous decrease of size. This in turn requires RF generators – the energy source for semiconductor manufacturing plasma processes – to deliver RF power with ever higher signal quality in respect of output power and time resolution. However, quality is costly. At the same time, suppliers of RF generators are under constant pressure to lower costs. This conflict in objectives is a classical engineering challenge that must be solved through innovation. In this paper, we will describe the main aspects of delivering accurate power levels to plasma chambers and measurement results regarding the newest generation of TRUMPF Hüttinger generators.

RF power signal quality

For TRUMPF Hüttinger, RF power signal quality includes the following aspects (see Figure 1):

- Accuracy of output power levels against a reference unit
- Repeatability of absolute output power accuracy across a customer order
- Variation of absolute output power accuracy over time and power cycles
- Drift of absolute output power accuracy over the calibration interval
- Suppression of harmonics
- Suppression of spurious signals
- Accuracy of timing and slope of signal

Absolute accuracy	▪ Deviation of a generator's output power from the definition of the International Systems of Units and the defined measurement standards of national institutes ▪ TRUMPF calibrates its generators against the definitions of NIST
Generator-to-generator repeatability	▪ Spread of output power of all generators produced ▪ The output power of each generator produced is measured after calibration and stored in a database
Process-to-process variation	▪ The drift of a generator's output power over a period of days and several power cycles ▪ Evaluated over one month and 70 power cycles
Drift of absolute accuracy over time	▪ Drift of a generator's output power over the recommended calibration interval of one year ▪ Evaluated over one year and 25 measurements per month
Harmonics suppression	▪ The quality of the output signal being free from harmonics of the generator frequency
Spurious suppression	▪ The quality of the output signal being free from spurious signals
Timing and slope of pulsing	▪ The ability of the generator to generate pulses of output power ▪ Rise or fall time ▪ Ability to generate any wave form

Fig. 1: Aspects of RF signal quality.

While the aspects of harmonics suppression, spurious suppression and timing accuracy of RF power for plasma applications have reached the expected levels, the accuracy of output power still appears to be a challenge.

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Drivers of RF power accuracy

When we speak of RF power accuracy, we distinguish between two classes of drivers:

1. Influences on the accuracy of generator calibration
   a. RF power measurement methodology
   b. Calibration of manufacturing calibration equipment
   c. Environmental conditions in manufacturing calibration
2. Influences on accuracy during operation
   a. Operating conditions in the semiconductor facility
   b. Stability of components
   c. Matching the generator to plasma impedance
   d. Generator control loop characteristics

Influences on the accuracy of generator calibration

RF power must be measured indirectly to be adequately accurate and affordable

At first glance, it seems surprising that RF power must be measured indirectly since many physical quantities can be measured with an accuracy of up to 10 orders of magnitude or even beyond. When it comes to higher frequencies and higher powers in the kilowatt range, however, problems not only arise from the precision and stability of the equipment, but also from the characteristics of the waveform itself.

In order to measure RF power, we must compare one of its physical effects to a defined standard. The simplest effect is the heat that results when RF is dissipated in a resistor. Heating the resistor to the same temperature by means of DC yields the required standard with known power since DC voltages and currents can easily be measured. This calorimetric approach is a pragmatic approach to measuring RF power without requiring the budget of a multinational research project.

Calibrating RF generators to deliver power at sub-percent accuracy requires a transfer standard of 0.5% accuracy and a floor standard of 0.65% accuracy

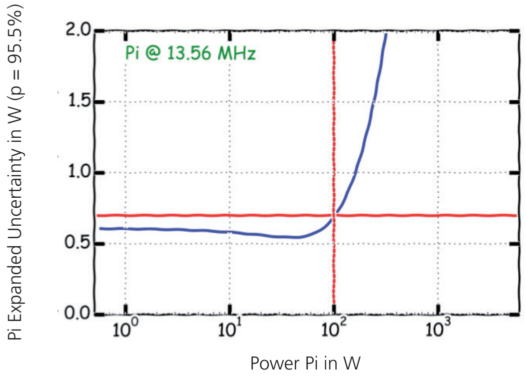
The calibrated device can never be more accurate than the standard it is calibrated against. In fact, the measurement uncertainty of the measurement standard defines the maximum accuracy of the calibrated device. The further away the floor standard in manufacturing is from the international measurement standard, the higher the uncertainty of the calibration result and the less accurate the generator (see Figure 2). TRUMPF Hüttinger uses power meters from RF Standard LLC for its transfer standard to ensure 0.65% accuracy on the manufacturing floor. The transfer standard is recalibrated every six months, and the floor standard is recalibrated every three months to ensure output power accuracy for all delivered products.

Calibration or Accuracy Hierarchy

BIPM	▪ International Bureau of Weights and Measures ▪ Maintains the International System of Units ▪ 1 Watt = 1 J · s^{-1} = 1 kg · m^2 · s^{-3}
NIST	▪ National Institute of Standards and Technology ▪ Provides standard materials, defines measurement methods, provides calibration services
RF Standard LLC	▪ Sells accurate power meters and operates a high-power, high-accuracy RF calorimeter (completely automated and NIST traceable)
Transfer Standard	▪ Transfer standard for deriving TRUMPF floor standard ▪ Recalibrated every 6 months at RF Standard LLC ▪ Accuracy is ±0.5% from nominal value
TRUMPF Floor Std.	▪ TRUMPF floor standard used to calibrate generators ▪ Recalibrated every 3 months against transfer standard ▪ Accuracy is ±0.65% from nominal value
Generator (Product)	▪ Generator is calibrated at last step of production ▪ Guaranteed accuracy of output power is ±1% from nominal value

Fig. 2: Driving an accurate floor standard for mass production.

Uncertainty of output power measurement below 100 W
in % versus W



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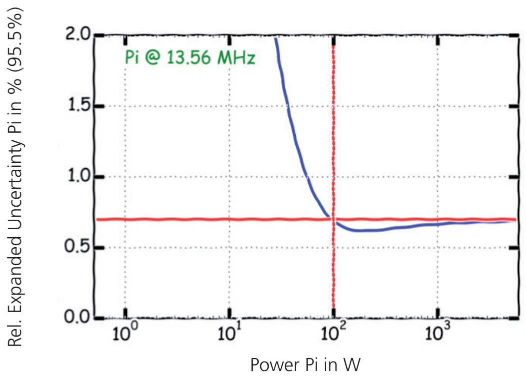

Fig. 3: Uncertainties of output power measurement under manufacturing conditions.

Robustness in the calibration process for highest accuracy
TRUMPF Hüttinger wanted to ensure delivery of accurate RF generators over larger manufacturing lots under changing environmental conditions such as humidity, temperature and the like. An investigation of the propagation of such changing environmental conditions pursuant to the Guideline to the Expression of Uncertainty in Measurement JCGM 100:2008 has shown that the developed calibration process is robust (see Figure 3).
The investigation results show that the TRUMPF Hüttinger calibration setup ensures a maximum calibration uncertainty of 0.65% against the National Institute of Standards and Technology.

Influences on accuracy during operation

Operating conditions in the semiconductor facility
Operating conditions in semiconductor facilities, called clean rooms, are subject to very tight specifications. Temperatures are around 20°C; the relative humidity is between 55% and 65%. In contrast, conditions are by far less strict in electronic manufacturing. Uncontrolled air flows from material transport in electronic manufacturing create greater variations in temperature and relative humidity compared to clean rooms. Thus, the uncertainty introduced by the operating conditions in the semiconductor facility is smaller than the uncertainty introduced in TRUMPF Hüttinger's manufacturing environment. The uncertainties are less than the numbers shown in Figure 3.

Stability of components
TRUMPF Hüttinger has selected strictly specified parts with low tolerances, low temperature coefficients (e.g. capacitors with NP0 ceramics) and with minimal aging. The combination of regular recalibration every 12 months, the design of a precise control loop (see below) and selected parts minimizes typical aging effects.

Matching the generator to plasma impedance
The net power supplied to the plasma is influenced by two drivers:
- The quality of the measurement of the reflected power to the generator
- The loss in the matchbox due to impedance transformation (matching)

An accurate measurement of reflected power is the basis for accurate delivery of power to the process; therefore, an accurate measurement is absolutely necessary. The quality of the measurement of the reflected power depends on the quality of the directional coupler in the output of the generator. TRUMPF Hüttinger uses an in-house designed coupler with a directivity of 60 dB and better. Each coupler is individually tuned to provide best performance. The tuning is performed either by tuning the coupling line of the coupler or by means of complex digital compensation in the measurement processor.

However, the matchbox is just as important as the generator for delivering accurate power to the process. Losses in the matchbox may be in the order of 5% to 10%, i.e. one order of magnitude larger than the inaccuracies introduced by the generator. The situation becomes worse when matchboxes tune to two different capacitor settings having the same complex impedances but causing different losses in the matchbox. This shortcoming must be addressed by means of measuring the power setpoint at the matchbox output and implementing the control loop over the entire system – generator and matchbox together.

Generator control loop characteristics

The TRUMPF Hüttinger control loop concurrently determines four setpoint deviations: forward power, delivered power, reflected power and DC bias. The algorithm always chooses the correct regulation dimension. The design challenge was to allow a high speed for offsetting the setpoint deviation while still guaranteeing the stability of the control loop. TRUMPF Hüttinger implemented an adaptive filter design to achieve both: high speed at large setpoint deviations and slow speed near target power for noise-free power signals. The chosen PI feedback control scheme ensures that the setpoint is reached quickly and very precisely. The output power always settles at the calibrated power even at a setpoint as low as 10 W. Output power accuracy over the complete temperature range is ensured by either the thermally controlled power detector PCB or a sophisticated digital compensation algorithm.

Output power histogram for TruPlasma RF 1003

In pcs per power band

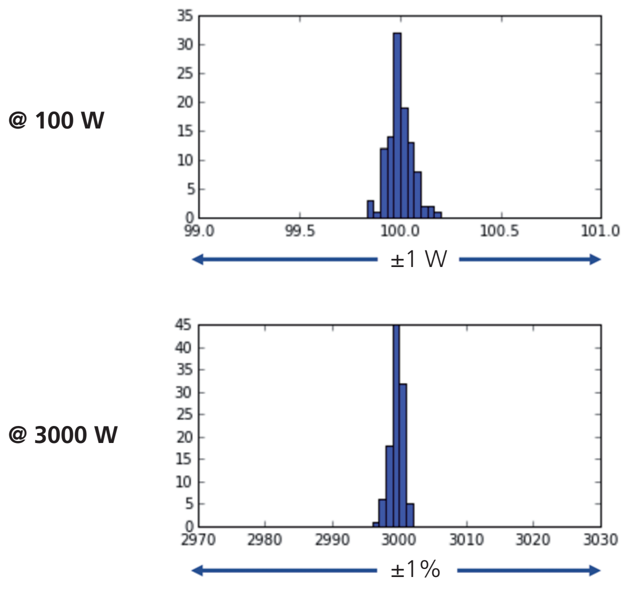

Fig. 4: Output power histogram of a manufacturing lot.

TRUMPF Hüttinger has taken care to make its generators the most accurate and the most stable in the market

TRUMPF Hüttinger floor standard is 0.65% accurate compared to NIST

TRUMPF Hüttinger achieves its 0.65% accurate floor standard by using

- a world-class transfer standard (±0.5%) based on measurement equipment from RF Standard LLC,
- an in-house developed calibration system with an ultra-linear A/D converter,
- a controlled manufacturing environment and
- a high-accuracy in-generator power measurement and regulation system (±0.2%).

TRUMPF Hüttinger typically calibrates 0.15% better than its floor standard

As shown by TRUMPF Hüttinger calibration statistics, our generators leave the factory in Freiburg (Germany) typically just 0.15% away from the TRUMPF Hüttinger floor standard (see Figure 4). This narrow

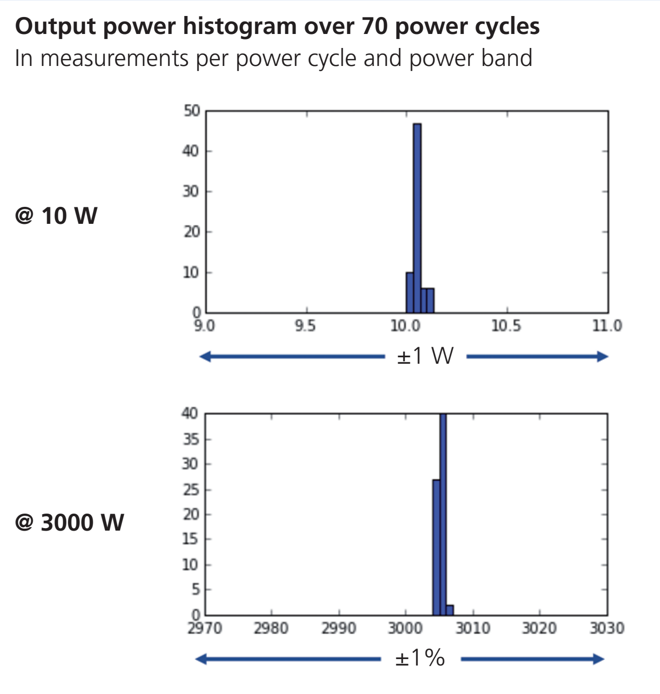

Fig. 5: Output power histogram over 70 power cycles.

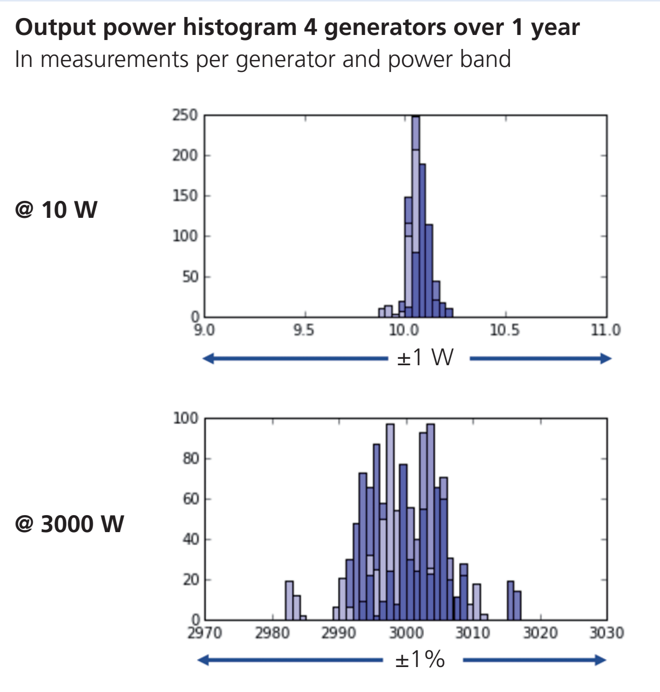

Fig. 6: Output power histogram over the calibration interval.

window of uncertainty for larger lots of generators allows TRUMPF Hüttinger customers to seamlessly replace generators without long recalibrations of the manufacturing process.

Generators from TRUMPF Hüttinger have a process-to-process stability typically better than 0.1%
The output power of a single TRUMPF Hüttinger generator typically drifts less than 0.1% between two operating phases. As can be seen in Figure 5, even after 70 power cycles the output power is still within a window of 0.1%. This low drift from power cycle to power cycle enables process stability and repeatability for TRUMPF Hüttinger customers.

The output power of TRUMPF Hüttinger generators is typically still 0.35% accurate after one year of operation compared to its delivery state
Narrow specifications and narrow-tolerance parts combined with thermal compensations and superior control loop characteristics result in superior, long-term accuracy in the output power of TRUMPF Hüttinger generators. As can be seen in Figure 6, even after one year of operation and 300 power cycles, the output power is still within a 0.35% window of the calibrated value from the manufacturing floor.

Summary

TRUMPF Hüttinger generators are typically as accurate as 0.75% compared to the NIST absolute power definition and typically 0.35% accurate over the calibration interval compared to the delivery state. As indicated earlier, we achieve an even better accuracy of the power delivered to the plasma chamber by controlling the entire system of generator and matchbox by means of one control loop. In this case, the setpoint deviation is taken either by power measurements at the input to a plasma chamber or by plasma field measurements in the plasma chamber itself. Further system optimization and larger potential cost optimizations can be achieved when process power suppliers, plasma chamber designers and process developers work closely together. This collaboration makes it possible to use fixed matches and auto frequency tuning to match process power supply to the plasma process.

Light and transparent:
TRUMPF Hüttinger Headquarters in Freiburg / Germany

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