DESIGN OF A 9MHZ 15KW CW AMPLIFIER FOR RHIC

Shane Dillon CTO

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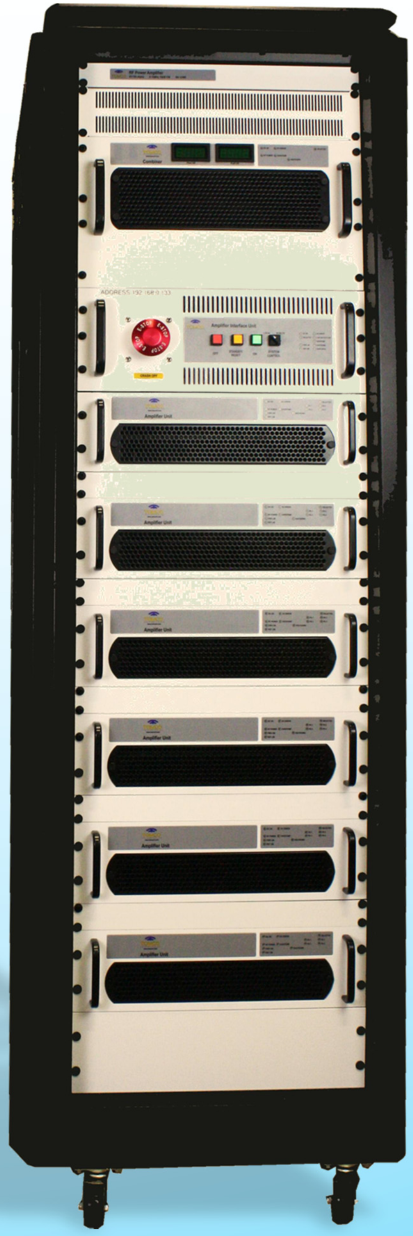
PHYSICAL CONFIGURATION

- Six 2.5kW amplifier units (water cooled)
- 6:1 combiner unit (water cooled)
- Interface unit (provides Ethernet, parallel, and local pushbutton interfaces).
- Switch mode PSU housed in a separate rack (located remotely outside of the accelerator tunnel to avoid risk of radiation damage)



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THE MAJOR SPECIFICATIONS.

<table>
<tr><td>Frequency</td><td colspan="8">9MHz ±10% minimum</td></tr>
<tr><td>Power</td><td colspan="8">15kW CW minimum</td></tr>
<tr><td>Gain/phase Linearity</td><td colspan="8">±1dB maximum and ±10° maximum from 15W to 15kW output</td></tr>
<tr><td>Harmonics</td><td colspan="8"><-30dBc at rated power</td></tr>
<tr><td>Stability</td><td colspan="8">Unconditionally stable over entire load space and dynamic range</td></tr>
<tr><td rowspan="2">Forward power at worst-case phase</td><td>SWR</td><td>1</td><td>1.5</td><td>2</td><td>3</td><td>5</td><td>10</td><td>infinite</td></tr>
<tr><td>kW (min.)</td><td>15</td><td>15</td><td>12</td><td>9</td><td>6</td><td>4.5</td><td>3</td></tr>
<tr><td>Load transients</td><td colspan="8">Withstands 100% reflection at full rated power for at least 100µs</td></tr>
</table>

THE DESIGN CHALLENGES

- Since circulators are not an option at 9MHz, the amplifier must be capable of withstanding the mismatch in its own right.

The design effort focused on four main areas:

- Achieving the forward power requirement safely
- Managing the heat
- Ensuring stability
- Staying inside the safe operating area

THE BASIC PROBLEM

As a first approximation, the maximum power that a push-pull transistor pair can produce is limited to **$2V_{dc}^2/R_L$**

V_{dc} is the DC supply voltage (fixed at 50 volts in this case)

R_L is the load resistance presented across the transistor drains (this is a function of the load at the output of the amplifier)

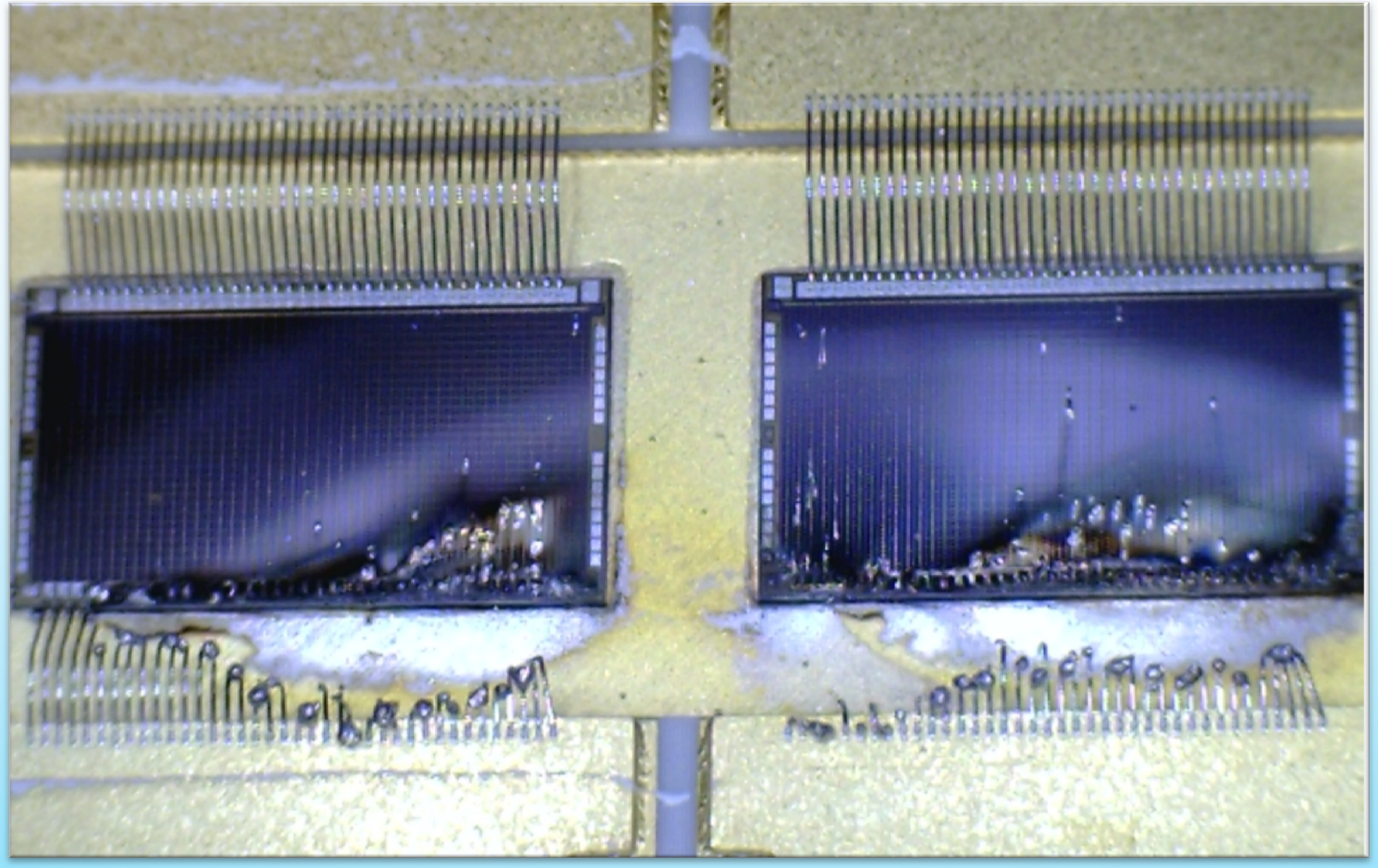
… the maximum available power is (roughly) inversely proportional to **R_L**

- If R_L is too large it becomes impossible to achieve the required output power.
- If R_L is too small a large amount of power can be produced but there is a risk of destroying the transistor due to excessive die temperature.

The design is a matter of balance between the high and low impedance extremes of the load space.

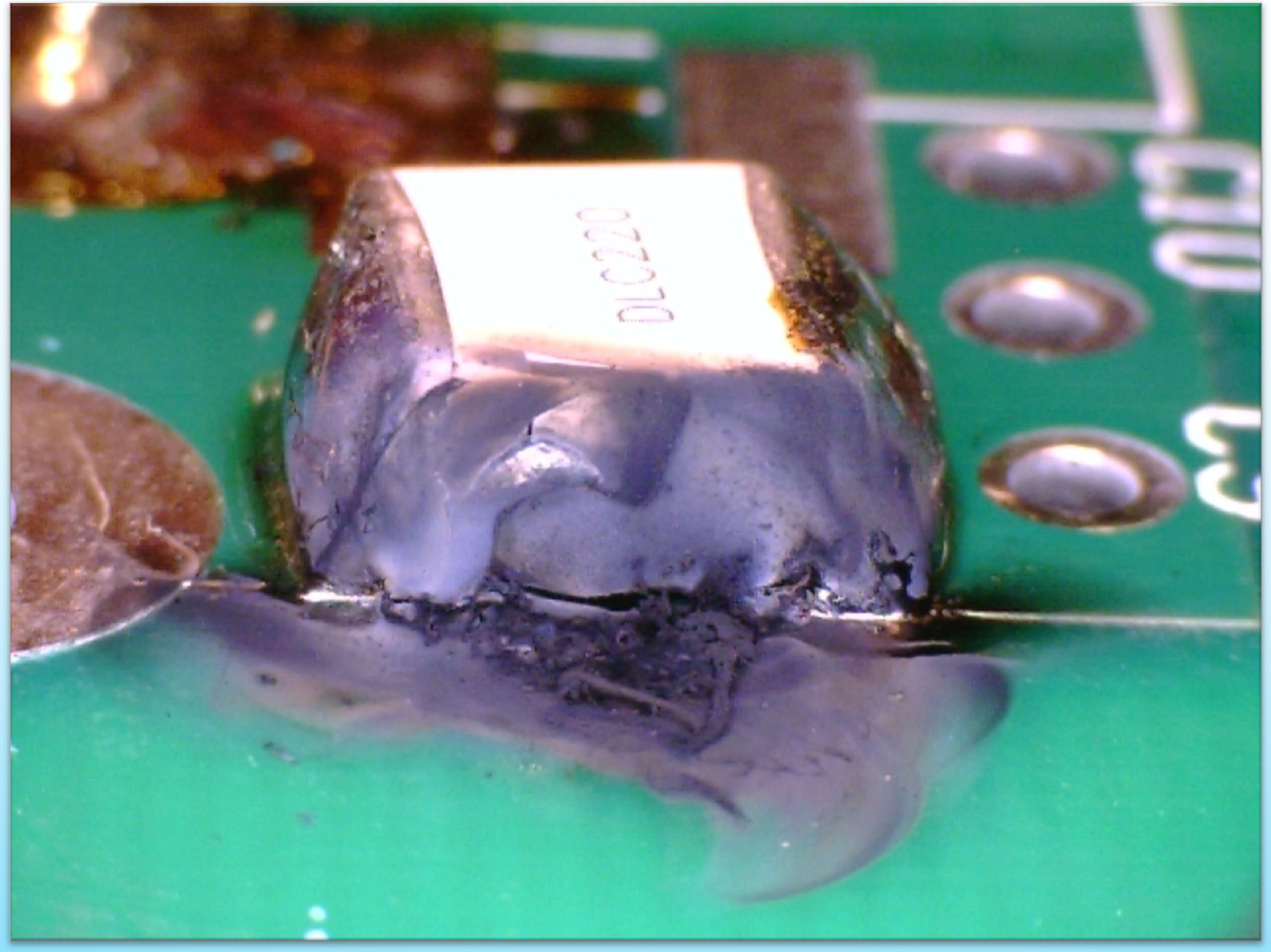
… THERMAL STRESS

- Reflected power disrupts the operating point of the transistor and can greatly reduce its efficiency.
- This can lead to very high heat dissipation in the silicon die, which if not properly managed can lead to a situation that will be very familiar to anyone who works with high-power amplifiers……



STABILITY

- LDMOS transistors have very high gain at low frequencies. This must be controlled to avoid possible oscillation.
- Since the load may be purely reactive, precautions were taken to limit the possible Q of resonances between amplifier circuit elements and the load. High-Q resonances can cause oscillations if any suitable feedback path exists.
- Uncontrolled resonances could destroy components such as filter capacitors or coupling capacitors, leading to another familiar scenario…………..



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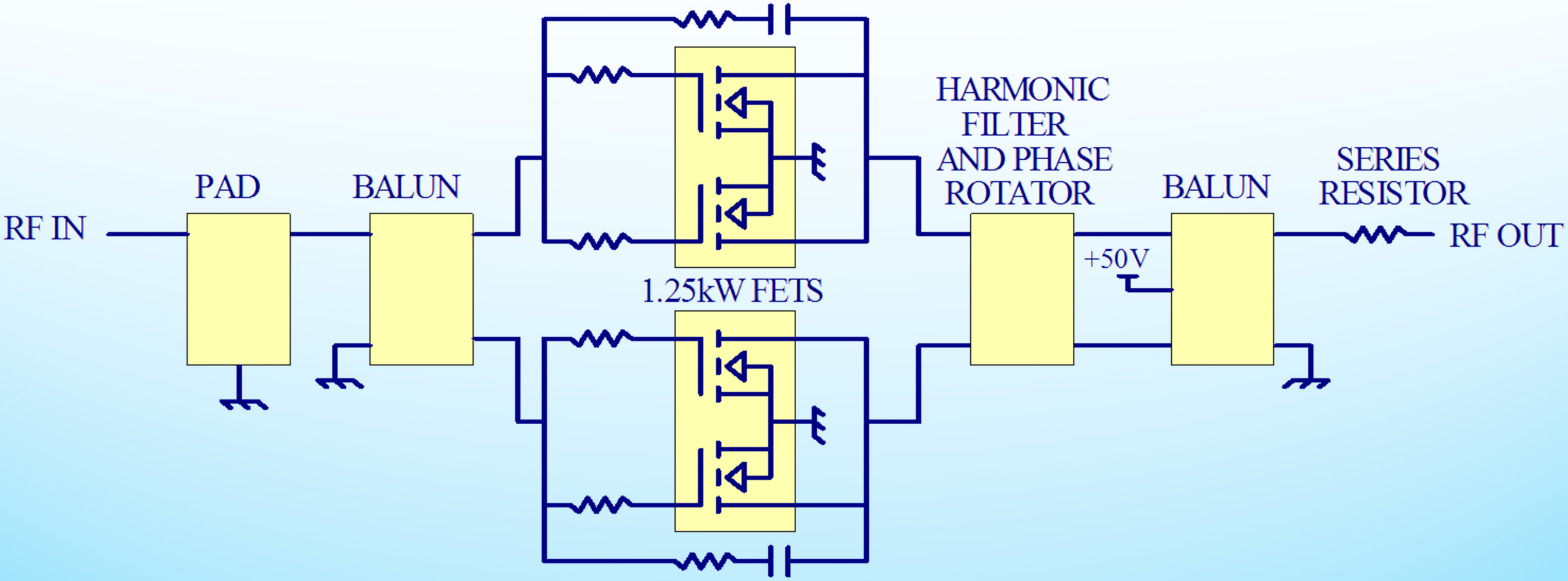
STABILITY

- Variations in the load impedance lead to corresponding changes in the linearity and gain of the amplifier. These effects must be minimised, to make the amplifier as "well behaved" as possible.

PA MODULE



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ACTUAL MEASUREMENTS:
THERMAL PERFORMANCE

- Thermal management involves a compromise between manufacturability, serviceability and thermal/electrical performance.
- The following three images show thermal measurements on a PA with the ceramic lid removed from one of its transistors.
- These 3:1 VSWR conditions represent some of the worst-case thermal stresses on the transistors.

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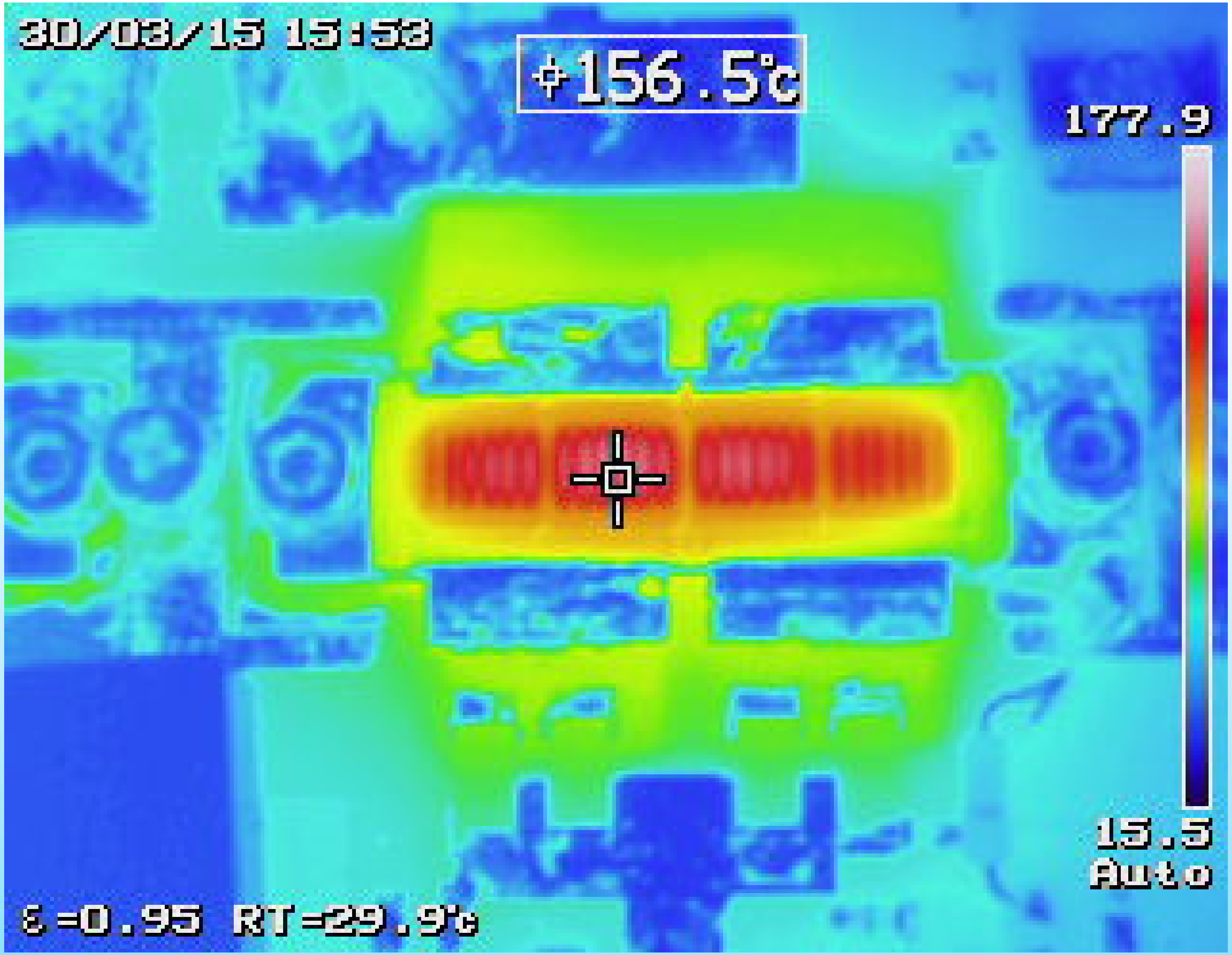
IMAGE 1.

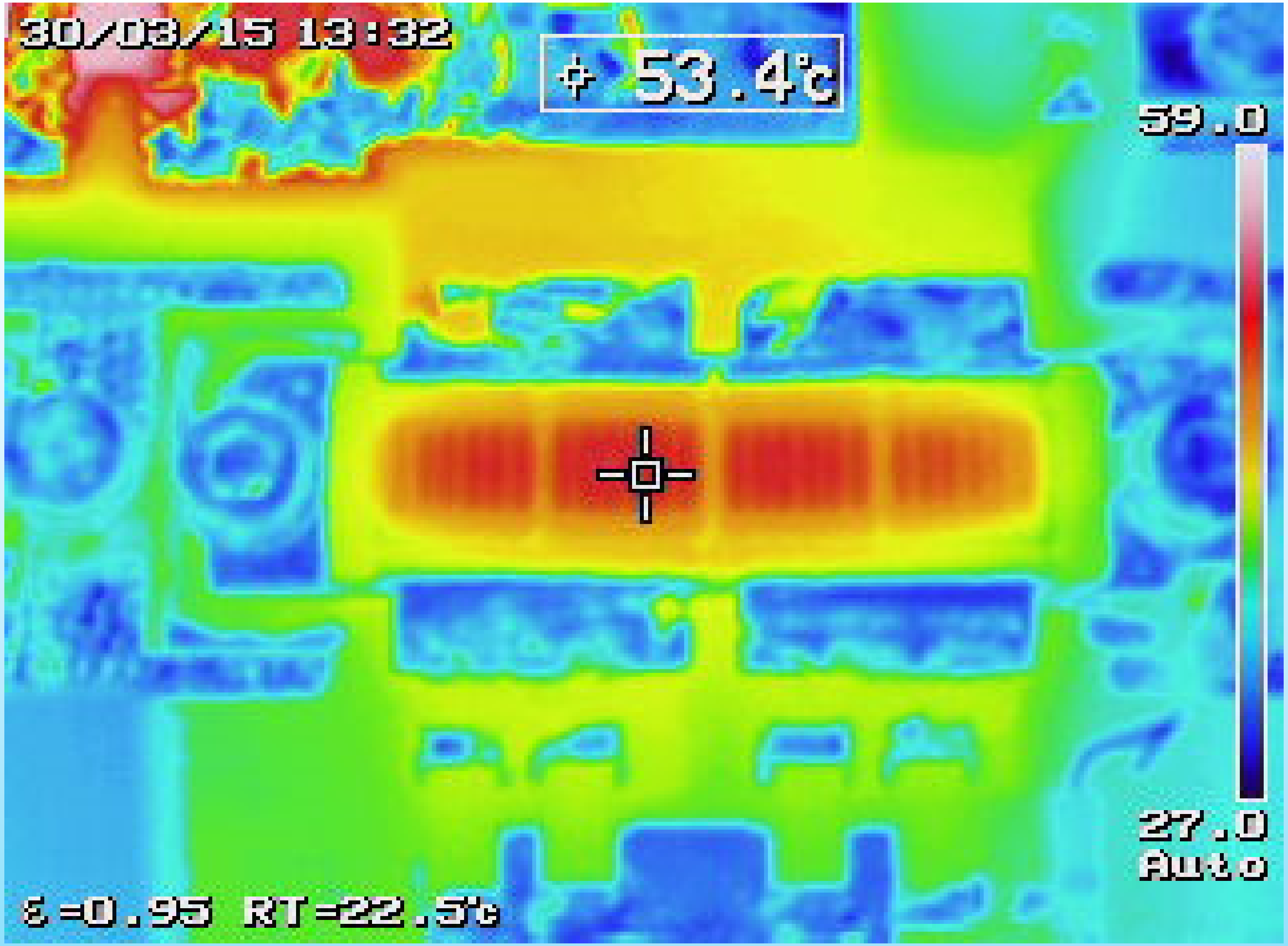
- Forward power 420 W
- 50 ohm load
- Die temp 90C

IMAGE 2.



- Low impedance load of SWR 3:1, again at a forward power of 420W
- Die temp 156C

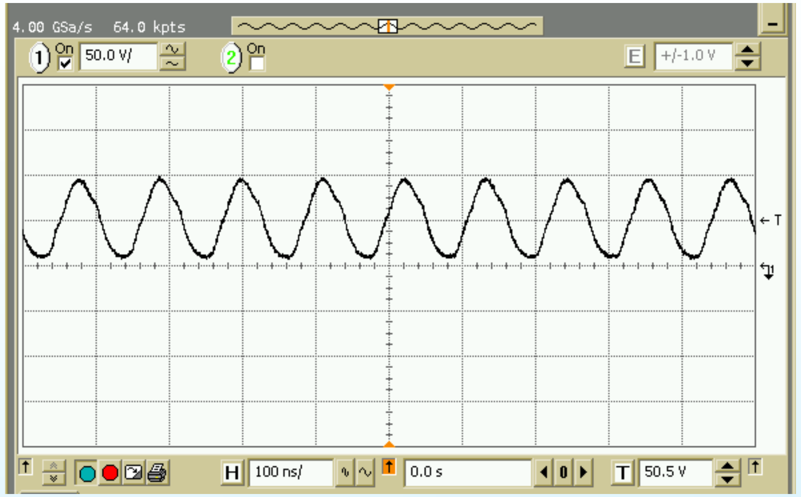
IMAGE 3.

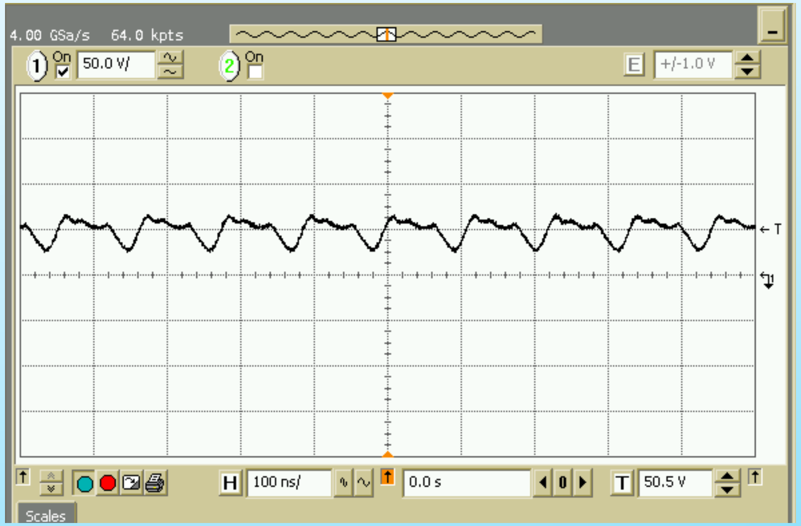


- High impedance load of SWR 3:1, again at a forward power of 420W
- Die temp 53C

TRANSISTOR VOLTAGE

Example of transistor drain voltage at two extremes of load impedance at infinite VSWR (50V/div):





- Upper screen = high impedance load. Forward power = 150W, supply current = 5.3A
- Lower screen = low impedance load. Forward power = 150W, supply current = 14A (the series resistor dissipates significant power in this condition)

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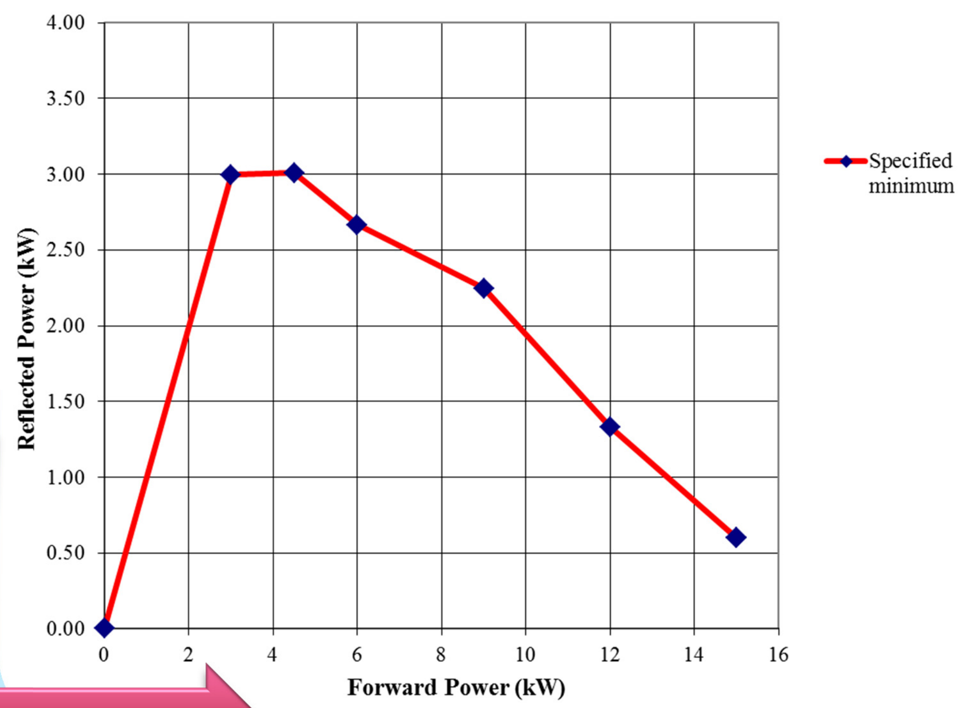
STAYING INSIDE THE SAFE OPERATING AREA- REFLECTED POWER LIMIT CONTROL

The specification implies that the reflected power the amplifier must withstand depends upon the forward power.

	Unconditionally stable over entire load space and dyna[illegible]							
Forward power at worst-case phase	SWR	1	1.5	2	3	5	10	infinite
	kW (min.)	15	15	12	9	6	4.5	3
	Withstands 100% reflection at full rated power for at l[illegible]							

$$P_{refl} = |\Gamma|^2 P_{fwd}$$



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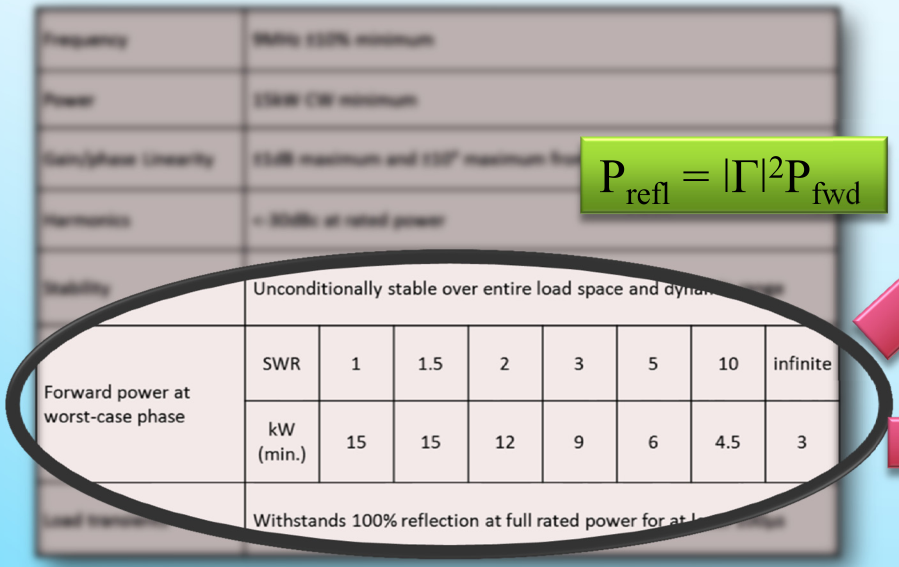
STAYING INSIDE THE SAFE OPERATING AREA- REFLECTED POWER LIMIT CONTROL

To achieve this the VSWR protection system uses an analog computation circuit that fits a 2nd order polynomial to the specified reflected power profile.



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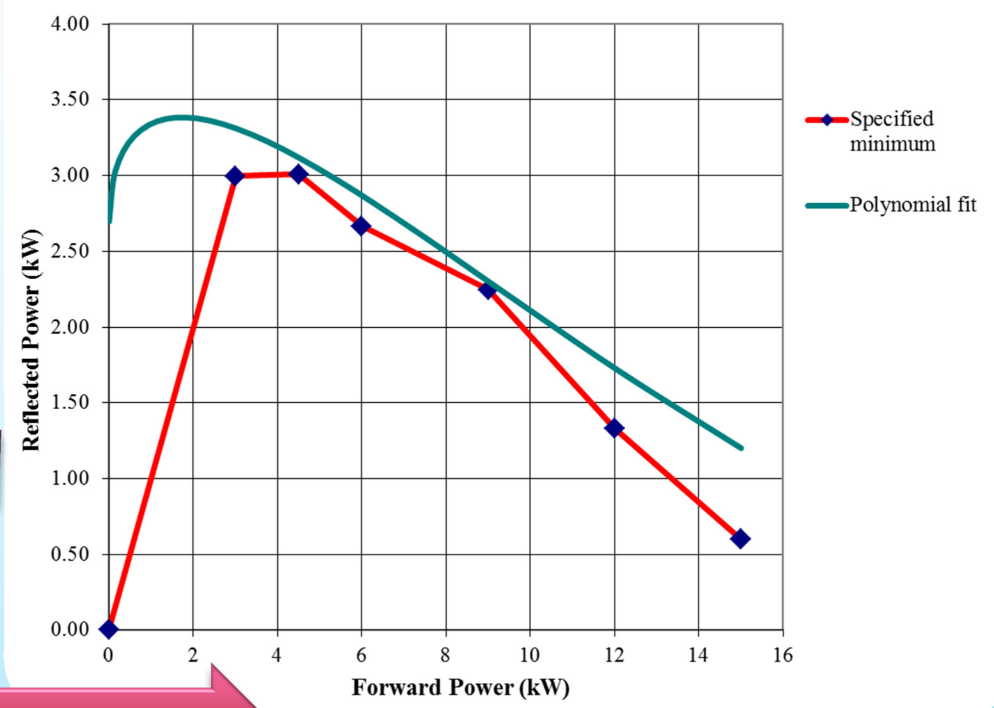

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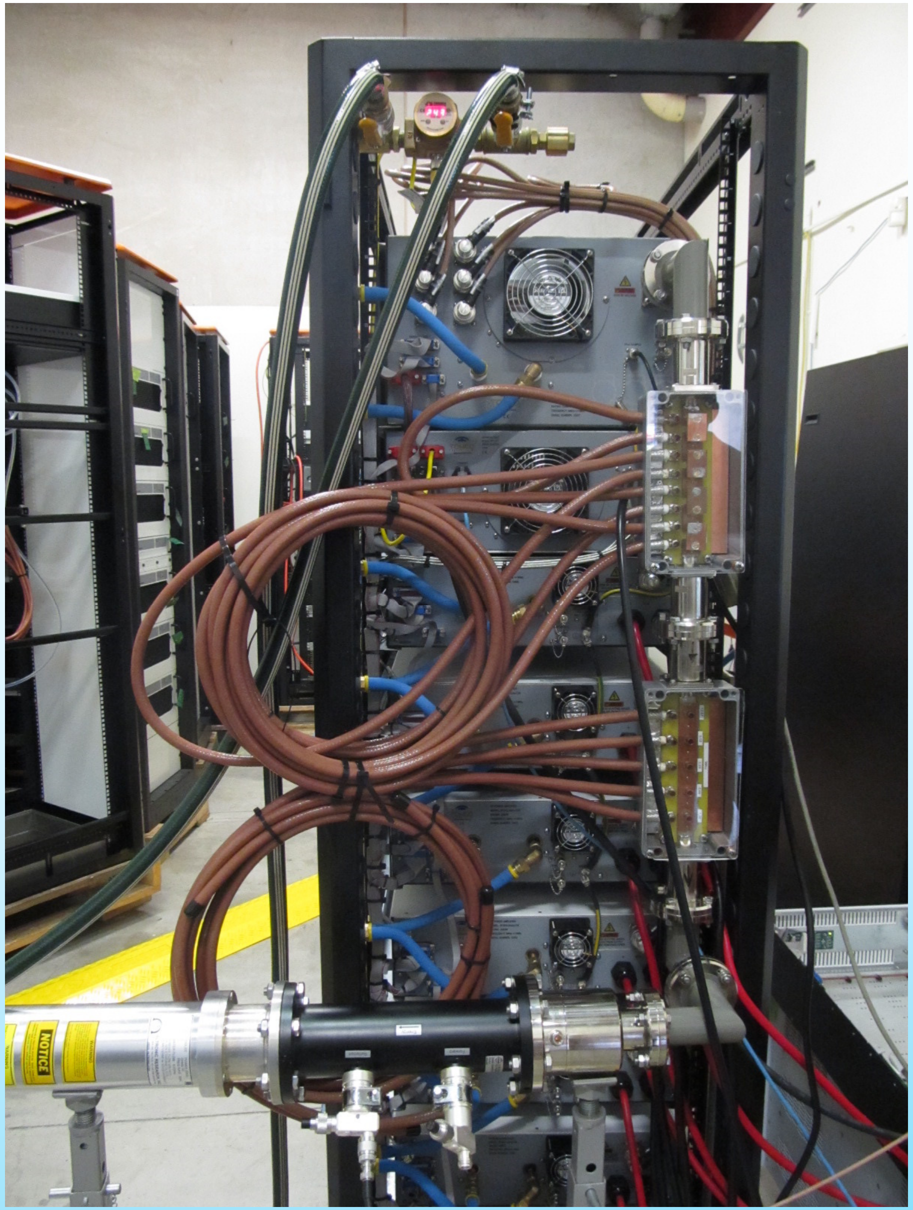
TESTING THE SYSTEM

- A 4-bit binary phase shifter and variable mismatch was constructed to allow testing over the entire load space.
- Gives 22.5° steps in reflection coefficient
- Allows six VSWR steps up to 10:1.
- For ∞:1 replace the dummy load with a copper plate!



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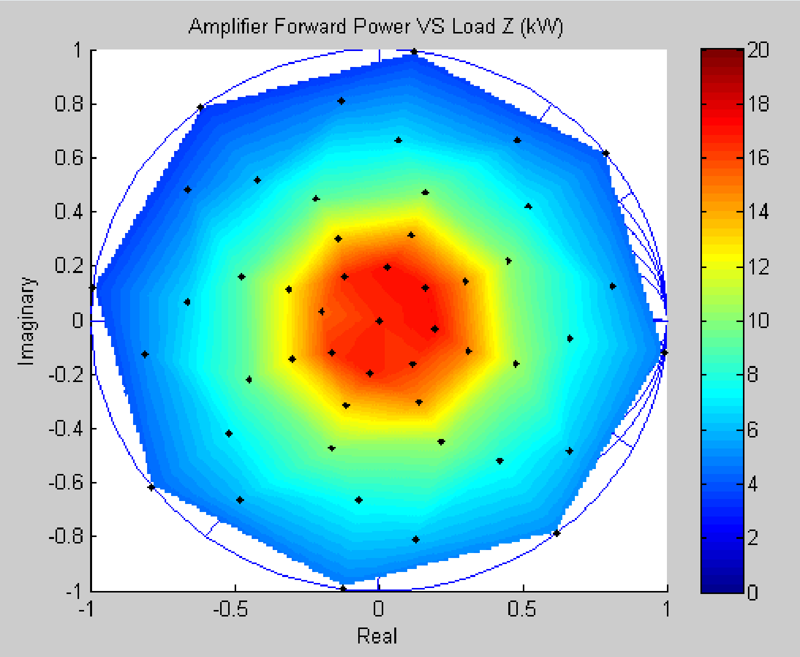
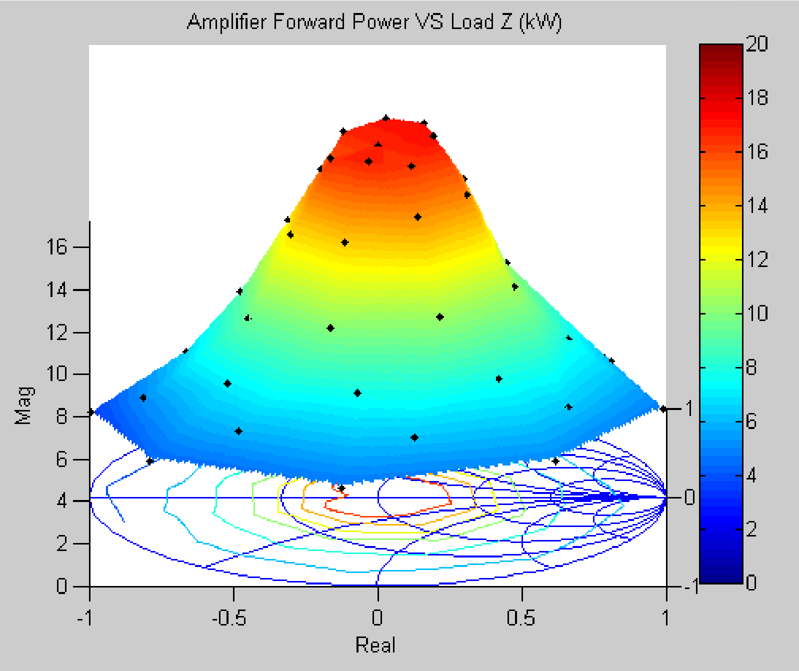
MISMATCH PERFORMANCE

- Plots of amplifier forward power (kW) across the entire load space.*





* Plots courtesy of Salvatore A. Polizzo, Brookhaven National Laboratory

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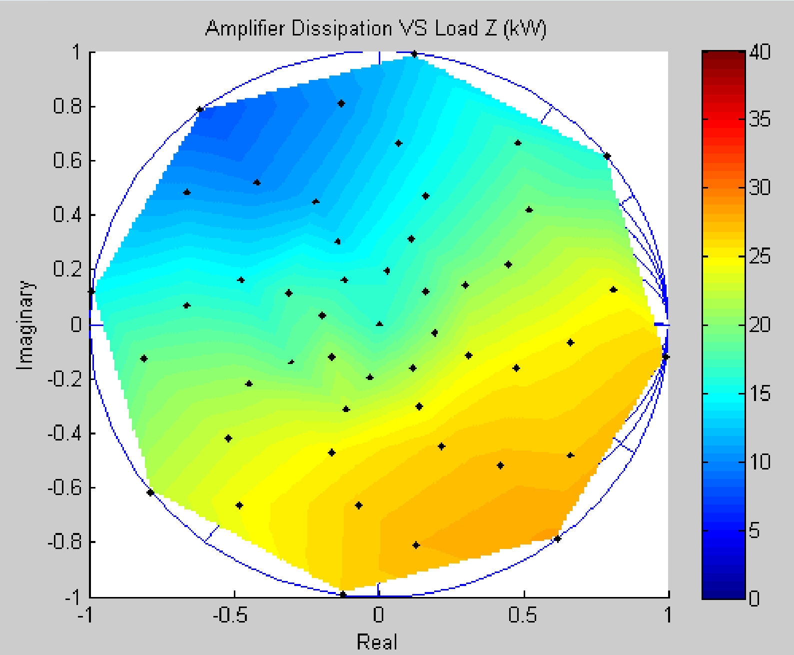
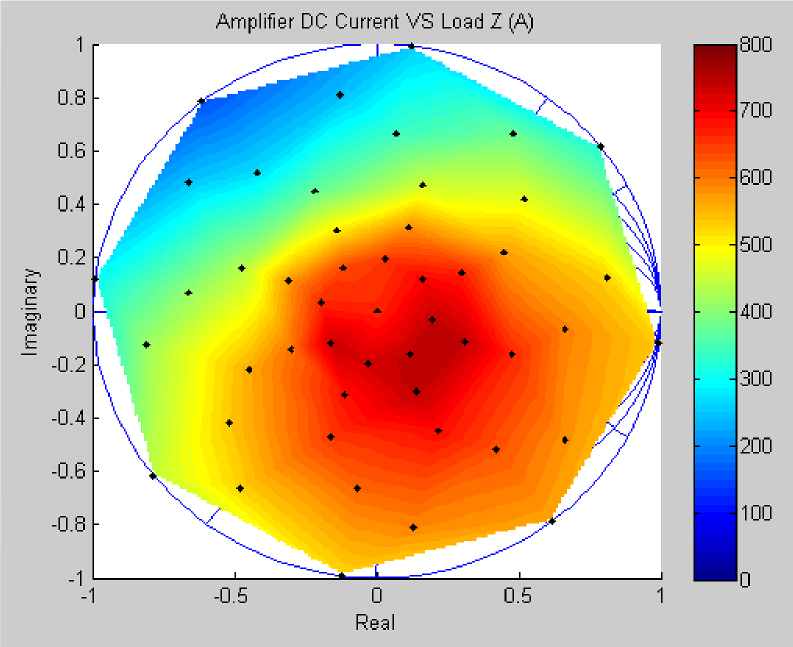
MISMATCH PERFORMANCE

- Plot of amplifier internal heat dissipation(kW) and DC current draw (Amps) across the entire load space.*

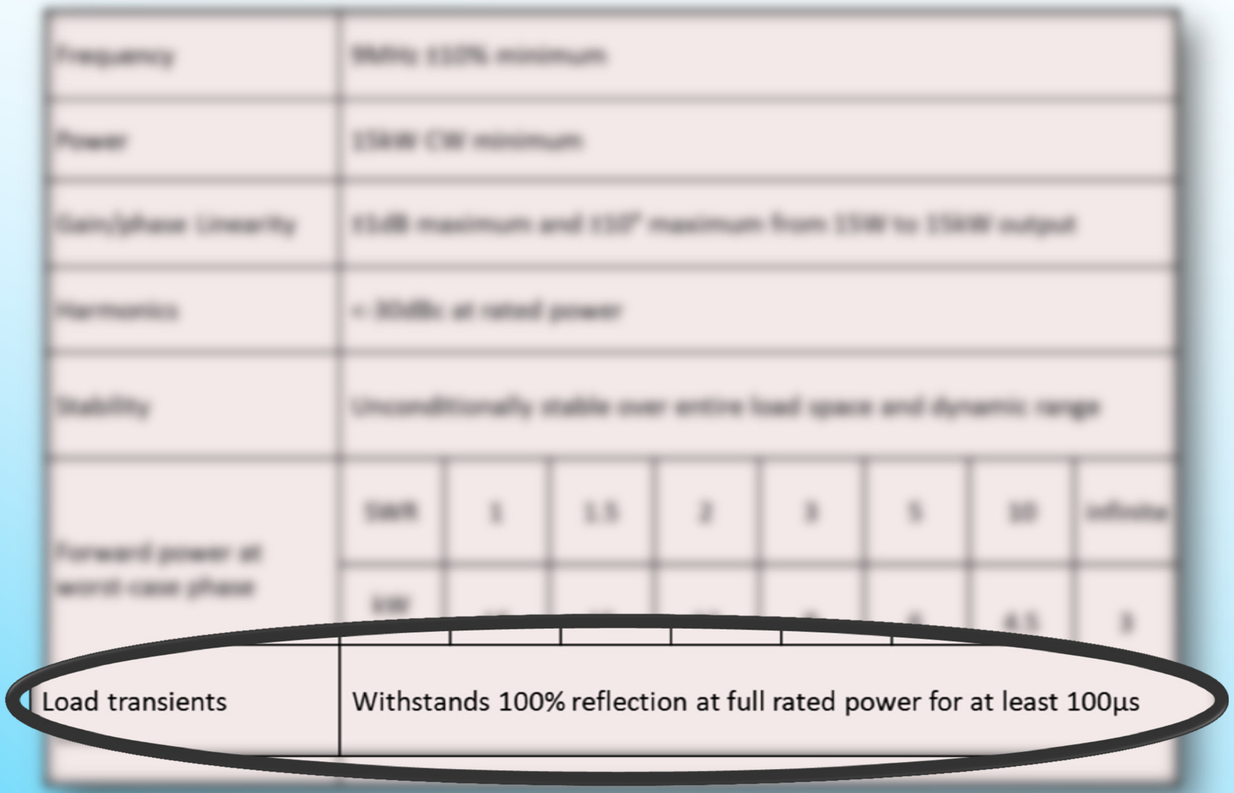




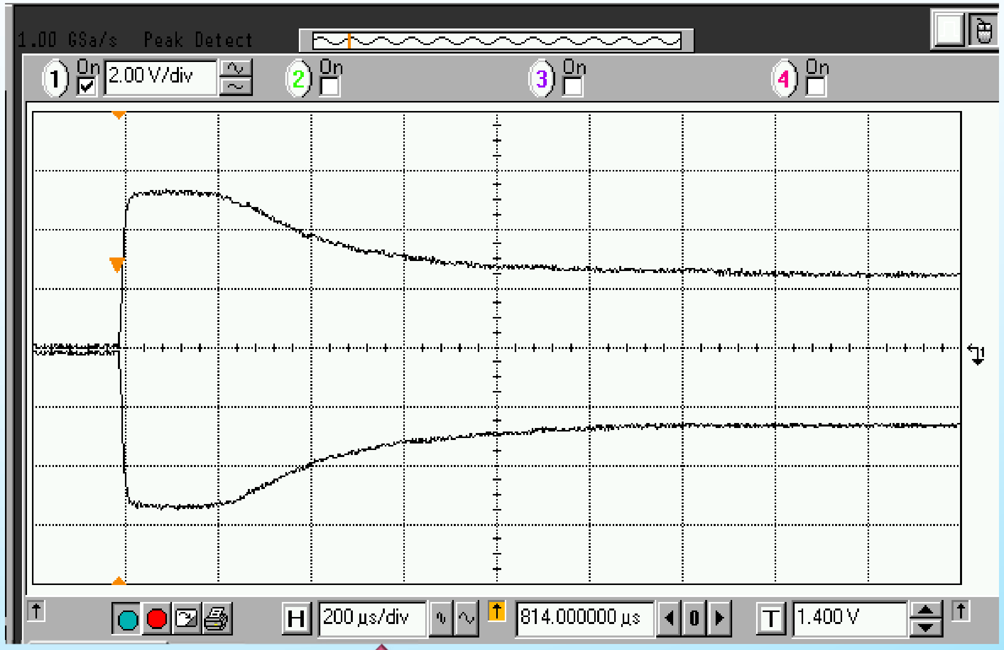
* Plots courtesy of Salvatore A. Polizzo, Brookhaven National Laboratory

TRANSIENT MISMATCH RESPONSE

- Tested by pulsing the amplifier into a short-circuit load

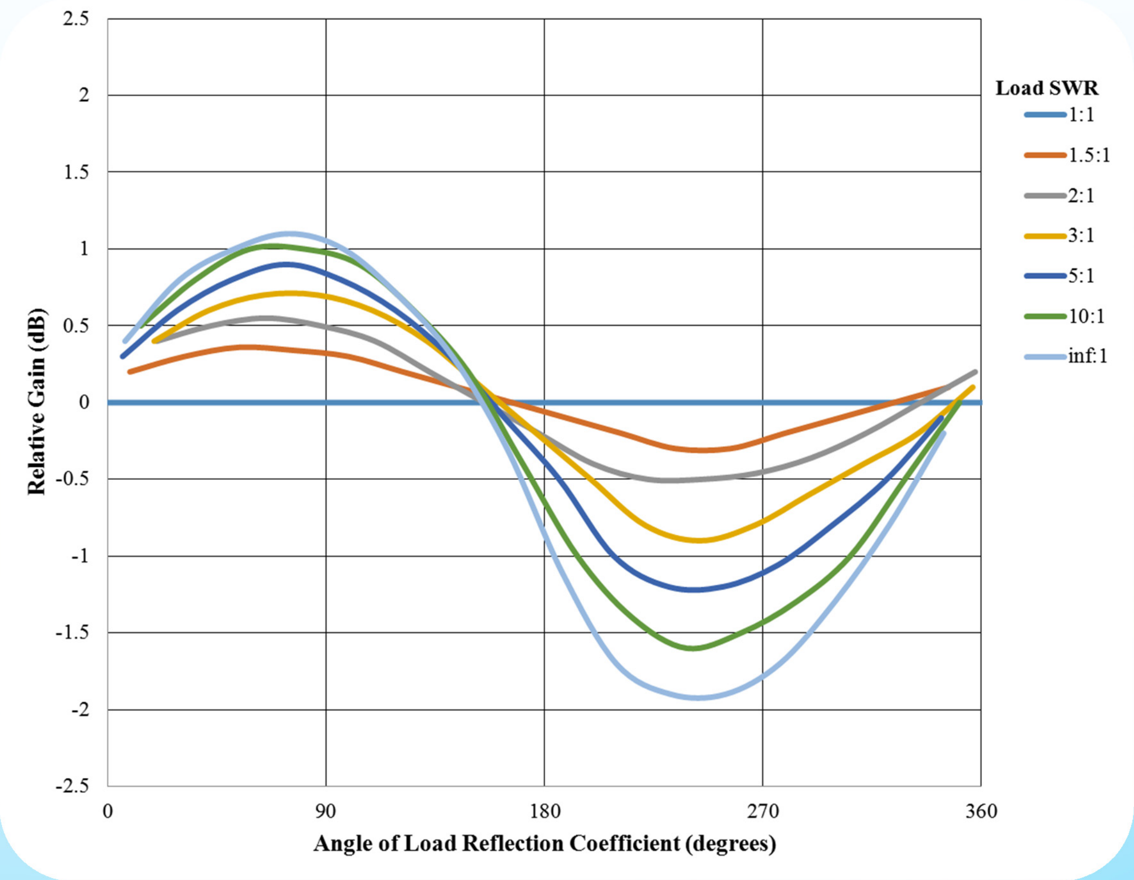


Load transients	Withstands 100% reflection at full rated power for at least 100µs



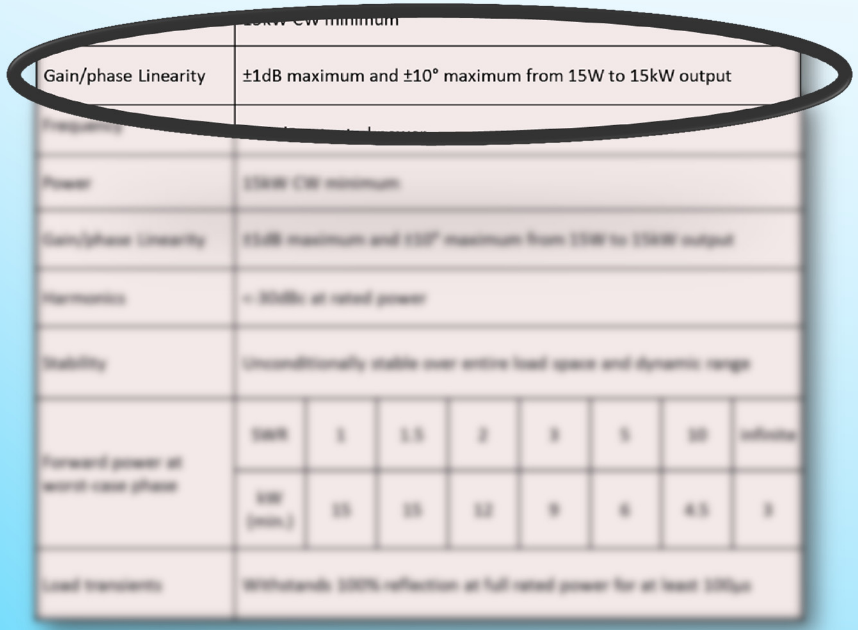
GAIN VARIATION WITH LOAD IMPEDANCE

- Graph shows gain variation versus angle of reflection coefficient from VSWR up to ∞:1.
- Worst case variation ±1.5dB.
- No discontinuities – well behaved at all impedances.

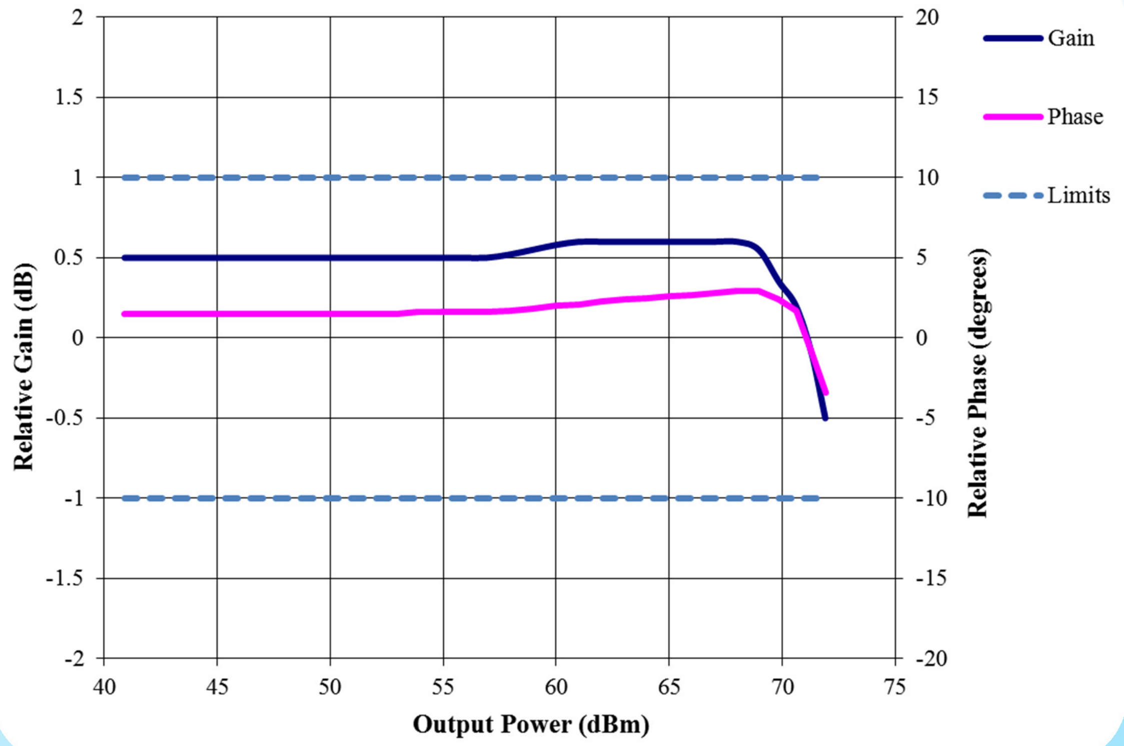


GAIN AND PHASE LINEARITY

- Gain and phase linearity over a 30dB range up to 15kW.
- Gain variation ±0.6dB
- Phase variation ±3°



Gain/phase Linearity	±1dB maximum and ±10° maximum from 15W to 15kW output



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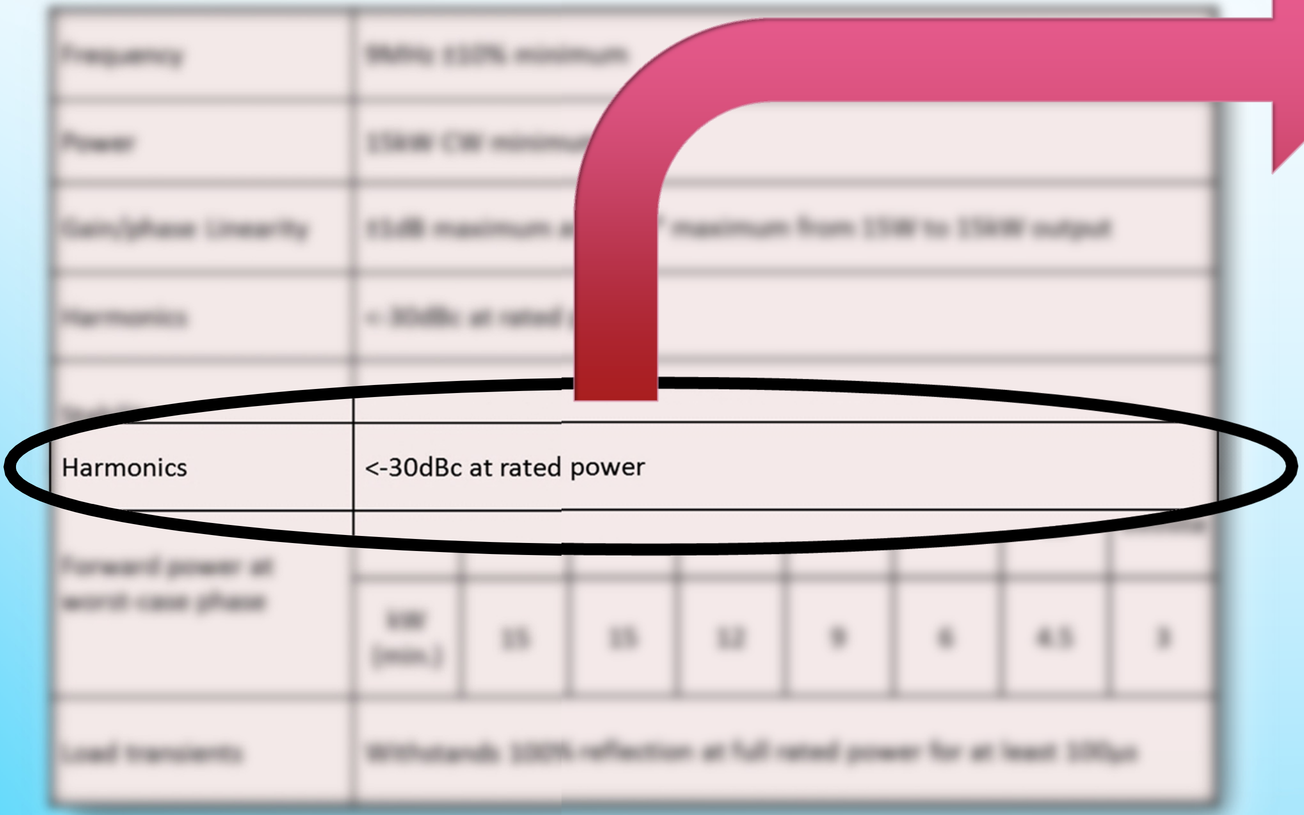
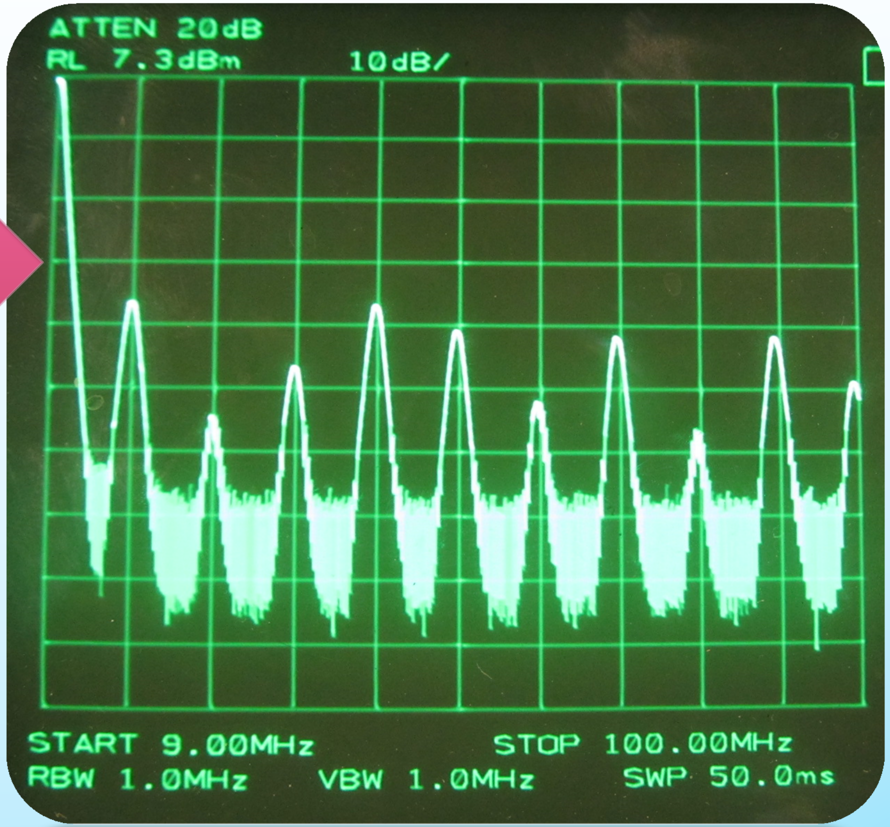
HARMONICS

- All harmonics <-35dBc at full rated power



Harmonics	<-30dBc at rated power



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THANK YOU!

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