352-MHz RF Power System Development at the Advanced Photon Source

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Present 350-MHz RF System Devices and Configuration

- **Five 1.1MW CW rf stations provide power to the APS accelerators:**

→ ***Each rf station utilizes one super-power klystron as a final amplifier***

→ ***One rf station powers booster, four power storage ring***

→ ***Each klystron requires a dc input power of ~ 90kV @ 20A dc to provide full output***

→ ***Klystrons are cooled by 450 GPM of DI water at 90ºF supply temperature***

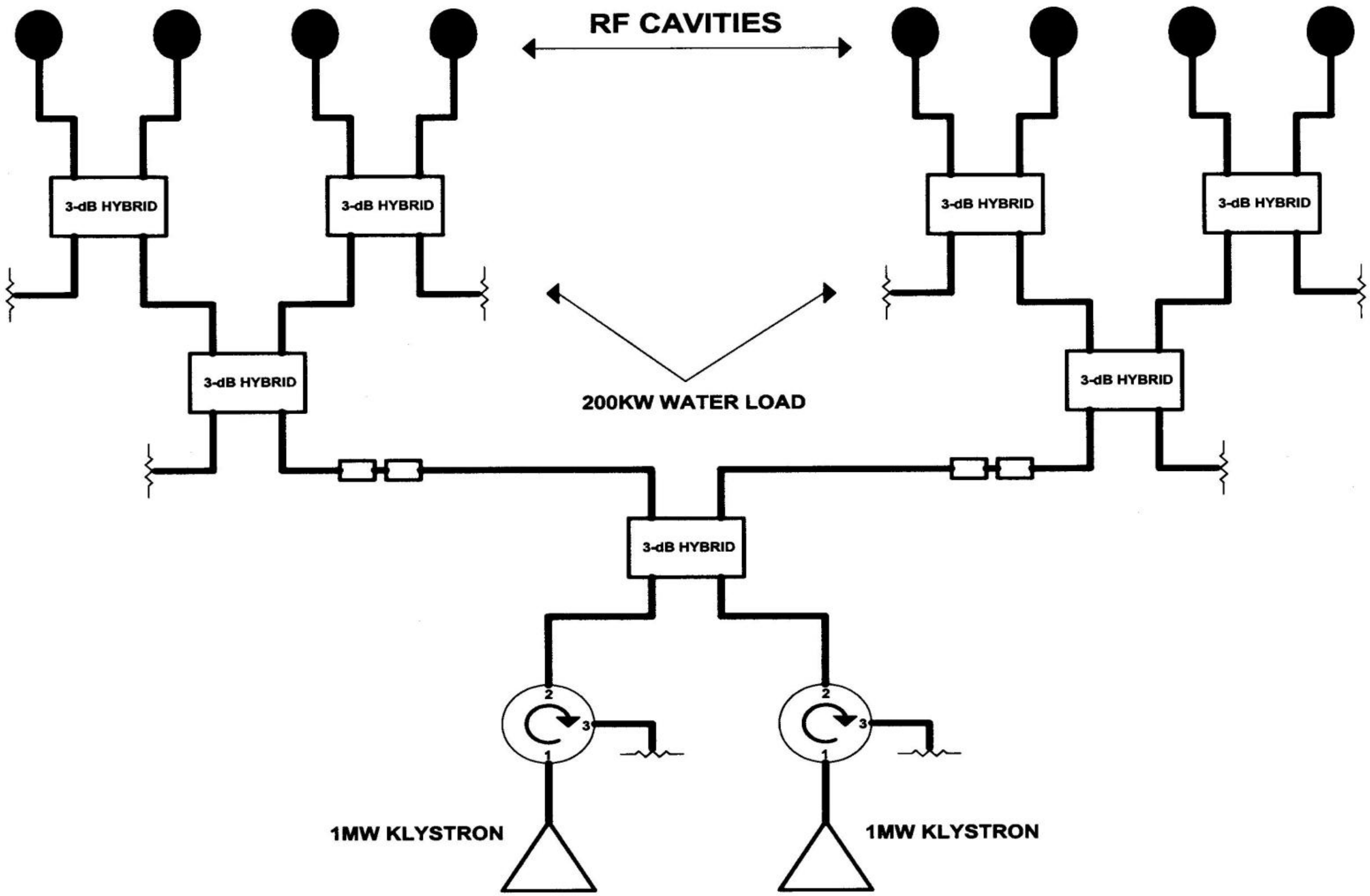
→ ***Typical rf output power for storage ring rf stations is ~ 600-700kW CW at this time***

352-MHz/1.1MW CW klystron inside x-ray shield enclosure

Typical rf system downtime is ~ 0.05 - 0.2%

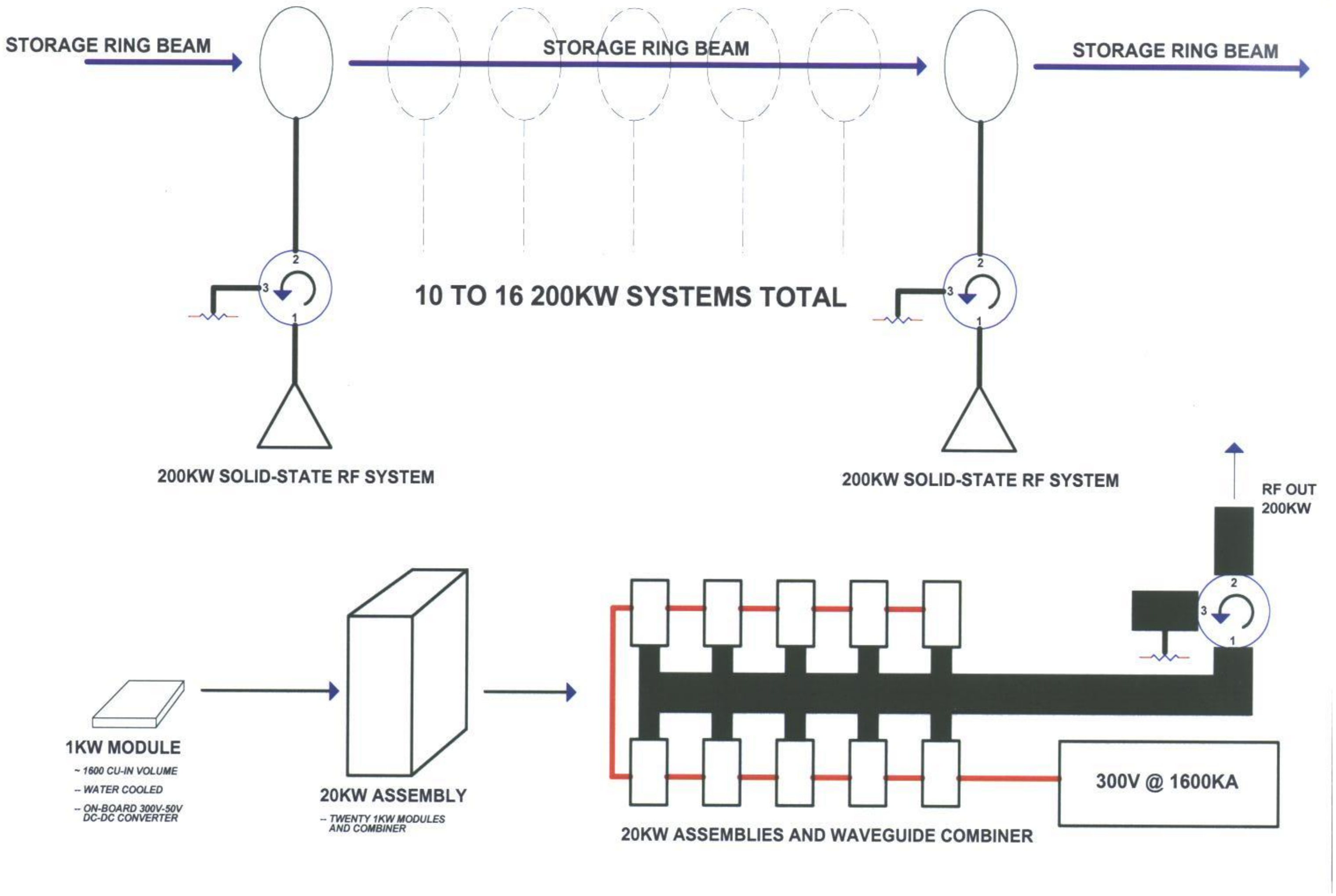
Present 350-MHz RF System Devices and Configuration

- The sixteen storage ring rf cavities are supplied rf power in two groups of eight, by either one klystron single-ended or two klystrons in parallel:



Proposed 350-MHz Solid-State RF System Configuration

The ultimate goal → A 200kW CW solid-state rf system utilizing combined 1kW modules:



Some 1kW Module Design Challenges

- **Greater than 99% reliability!**
  - → *One device per kilowatt or two?*
  - → *Thermal issues:*
    - -- *Is 1kW right at the limit of transistor package?*
    - -- *Cooling of board and passive components*
- **Development of on-board 1kW circulator and load**
  - → *May get from industry, but at what cost for initial units?*
- **Primary input power:**
  - → *On-board DC-to-DC converter, or 480VAC to each module?*
  - → *Design of 300V/50V dc-dc converter……..buy from industry or design in-house?*

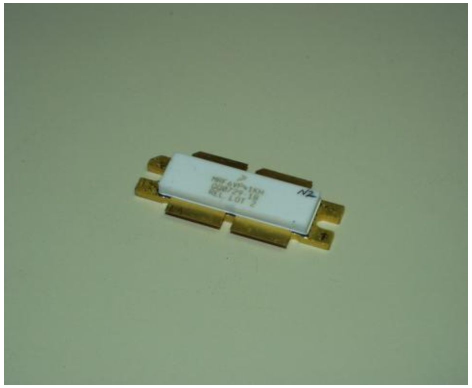
APS 352-MHz/4kW Combined-Amplifier Solid-State Demonstration Project

- Goal and Purpose:
  - → Demonstrate a 352-MHz 4kW CW combined solid-state amplifier system
  - → Determine practical power output limit from single part
  - → Produce baseline data to estimate the feasibility, cost, and MTTF of a 200kW combined-amplifier system
- Duration:
  - → Two years, FY09-FY10

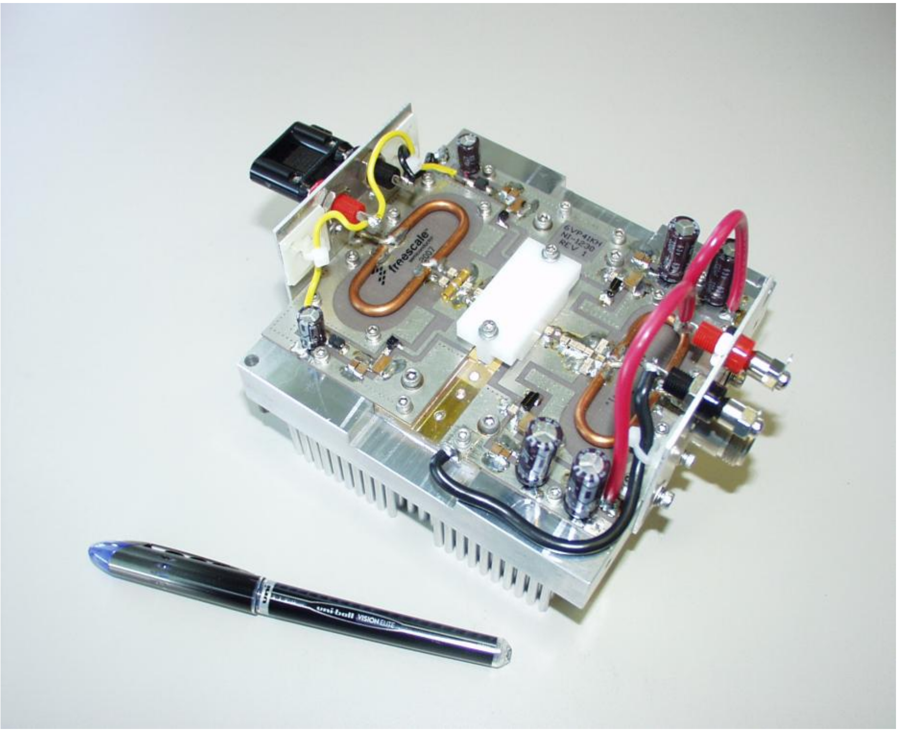
Proposed Design Features of 1kW Module

- Capable of 1kW CW continuous output at 351.93MHz
- Operating bandwidth = 1MHz
- Gain = 30dB
- Linearity → 3rd order IMD -25dBc or greater
- Efficiency = 55% minimum
- Load Sensitivity → Able to operate at maximum power output at full reflection at all phase angles without damage
- Water cooled with existing de-ionized water system
- Internal 300V/50V DC-DC converter
- Internal 1kW circulator with load
- Volume ~ 1600 cubic inches (?)
- Capable of being removed from system with power applied
- Smart control system with diagnostic capabilities
- 99% reliability required

Initial Tests of the Freescale MRF6VP41KHR6 Device



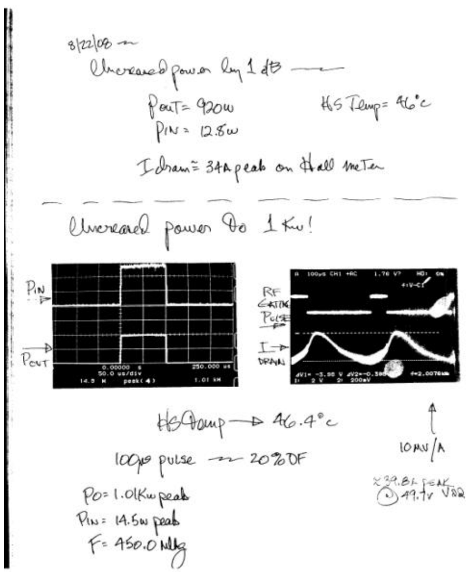
- Published ratings for the LDMOS push-pull transistor were for pulsed service:
  1kW peak,100us pulse, 20% duty factor…………

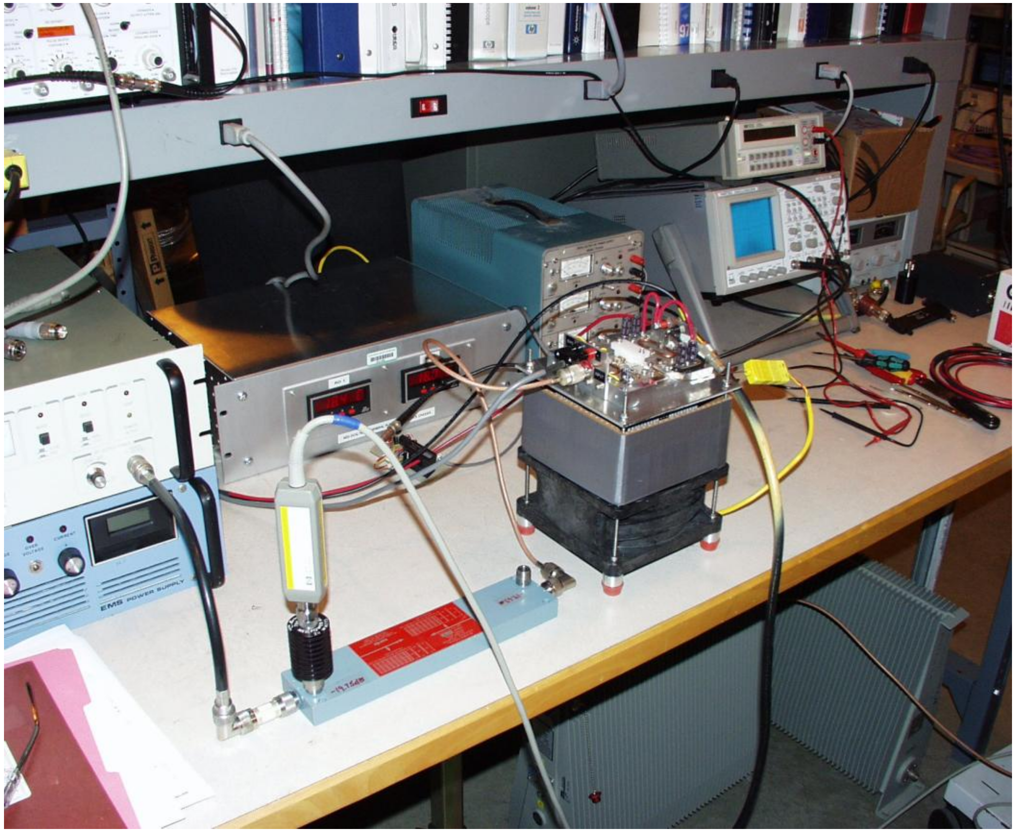


- We obtained a 450-MHz evaluation board kit from Freescale and tested it at rated power.

Initial Tests of the Freescale MRF6VP41KHR6 Device

- The evaluation board produced 1kW peak power at 450MHz, 100us, 20%DF with no problems!
- I increased pulse width to 50% DF and the amplifier survived.........
  → *but passive components in output network were overheating.*

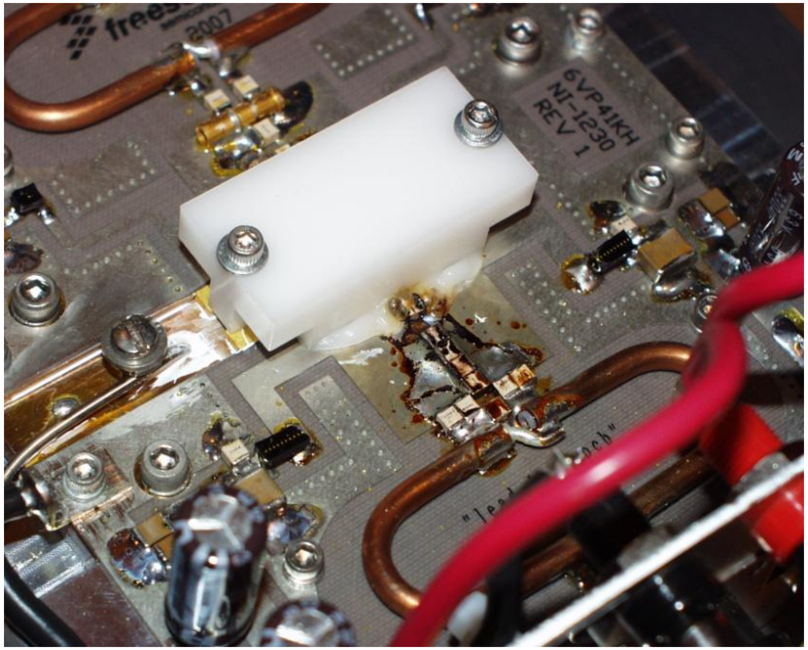


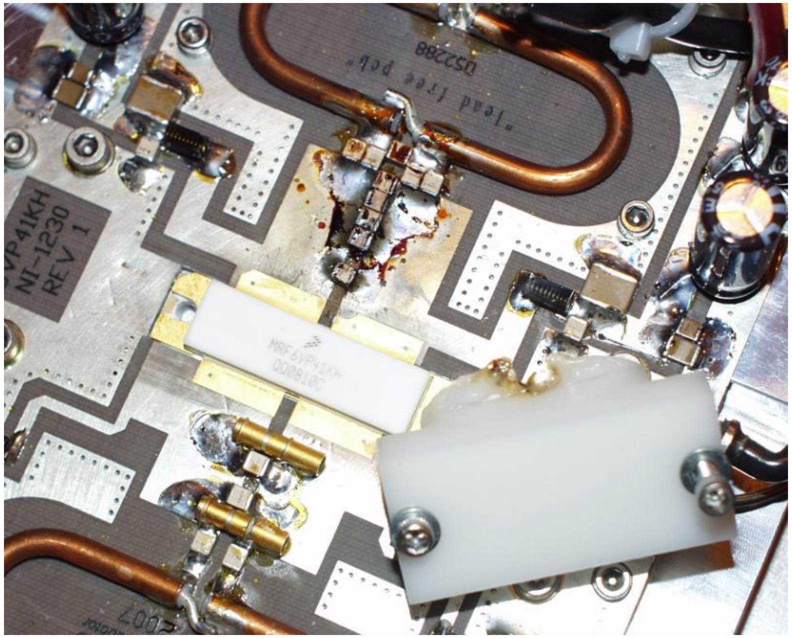


Amplifier test setup showing Forced-air cooling of "pin fin" heat sink

Initial Tests of the Freescale MRF6VP41KHR6 Device

- Operation at 50% DF ended after approximately 10 minutes when the transistor was destroyed because of arcing on the drain leads.
- *Excessive circuit board temperatures melted the delrin clamp that was holding the transistor drain leads to the circuit board foils.*





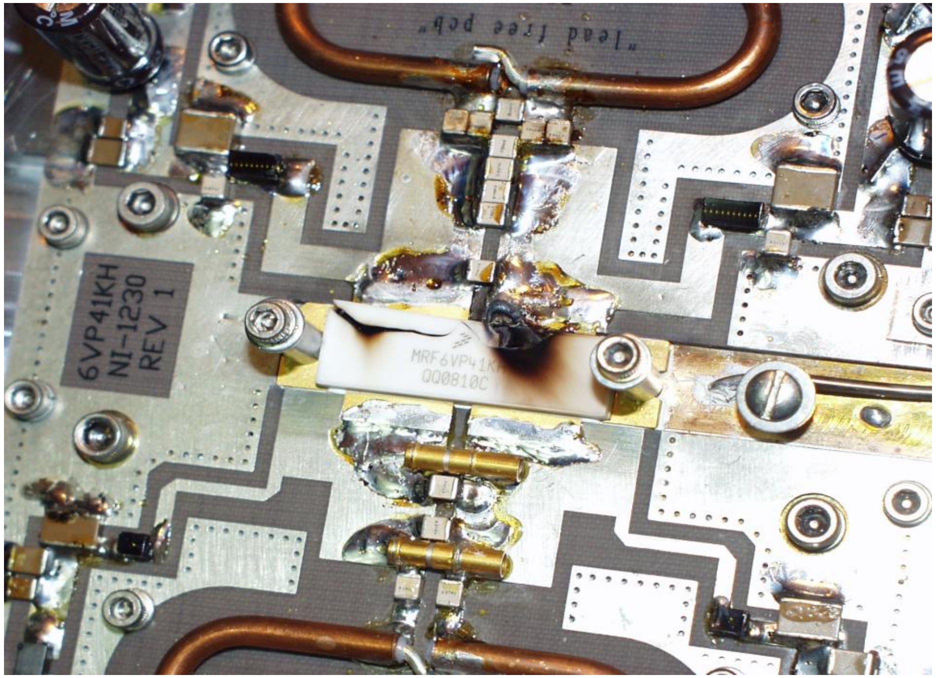
Initial Tests of the Freescale MRF6VP41KHR6 Device

- The transistor was replaced and the leads were soldered to the board foils to eliminate the need for the delrin clamp.
- Operation at 1kW / 50% duty factor was successful.
- CW power was attempted, but the transistor failed after approximately seven seconds at ~ 400 watts CW output.

CONCLUSION:

→ Efficient water cooling should allow CW operation

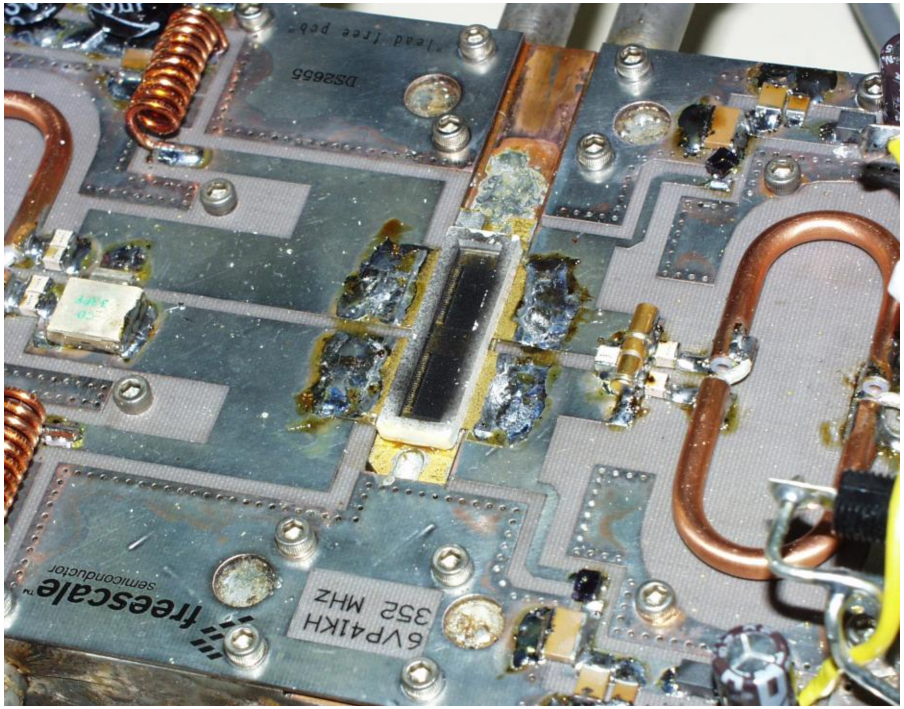
→ Will cooling with 90ºF water be acceptable?



Initial Tests of the Freescale MRF6VP41KHR6 Device

- Freescale tested the MRF6VP41KHR6 device using a water-cooled copper cold plate and demonstrated 1kW CW output power at 352.21MHz

- We obtained two Freescale MRF6VP41KHR6 352.21MHz/1kW evaluation boards and assembled two amplifiers using “de-lidded” transistors supplied by Freescale



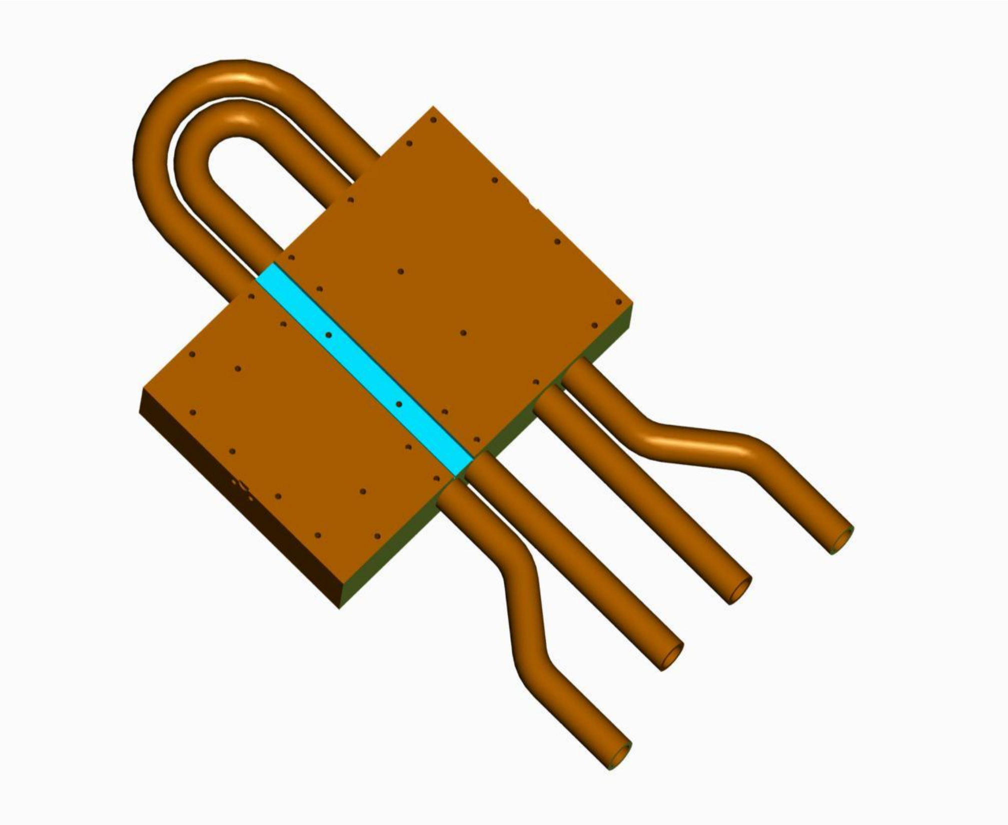
- We designed an improved copper cold plate for higher thermal efficiency.

FY09 352-MHz 1kW CW Amplifier Test Plan

- **Two Freescale 352-MHz/1kW CW water-cooled MRF6VP41KHR6 test amplifiers were built:**
  - → ***One with soldered part***
  - → ***One with clamped part***

- **Improved APS cold-plate design was utilized**

- **We directly measured transistor die temperature to arrive at the estimated MTTF for a combination of:**
  - → ***Transistor mounting techniques***
  - → ***Thermal performance of "carrier" design***



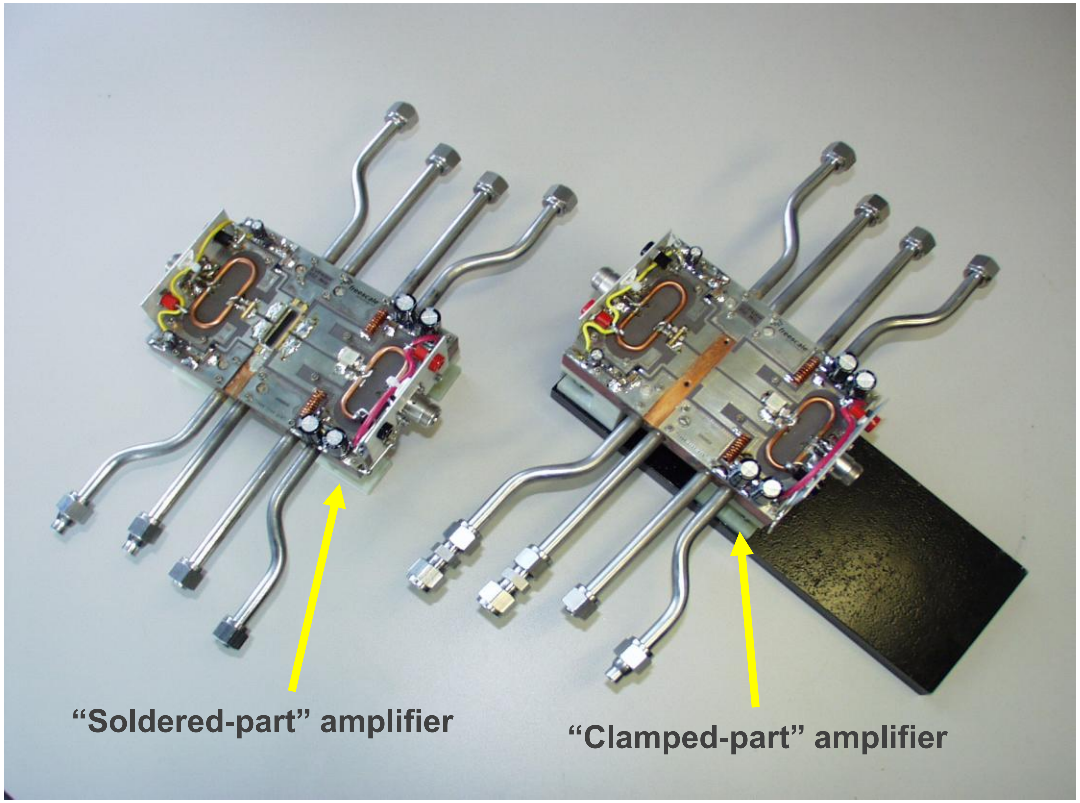
Modified APS cold-plate design

352-MHz 1kW CW Amplifier Construction

- **Construction of the amplifiers was difficult due to the thermal capacity of the copper cold plate.**

→ Assembly soldering had to be done in stages using a hot plate and a 200-watt soldering iron

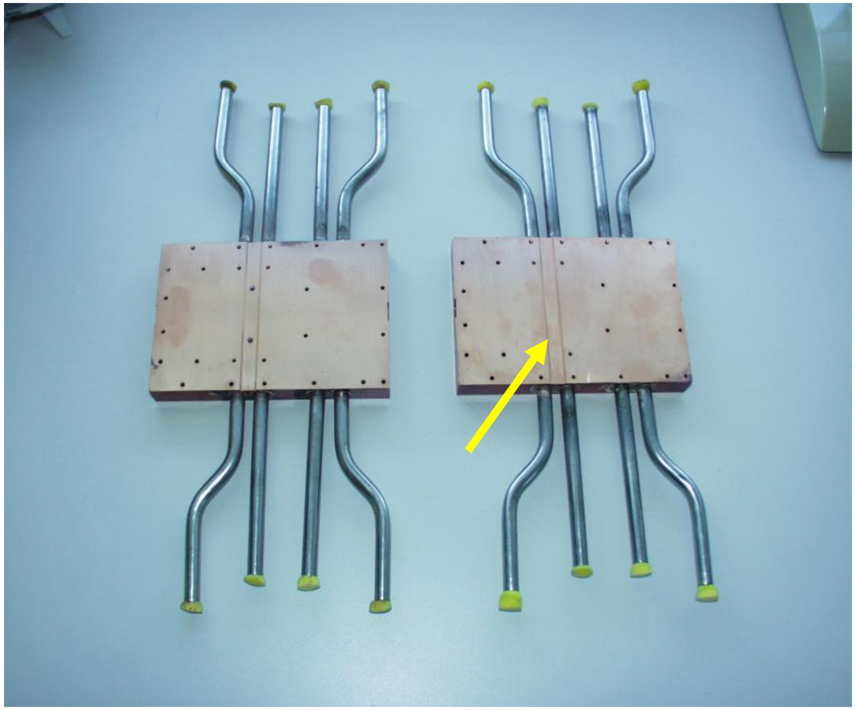
→ Assembly was performed in stages using two solder alloys with different melting points

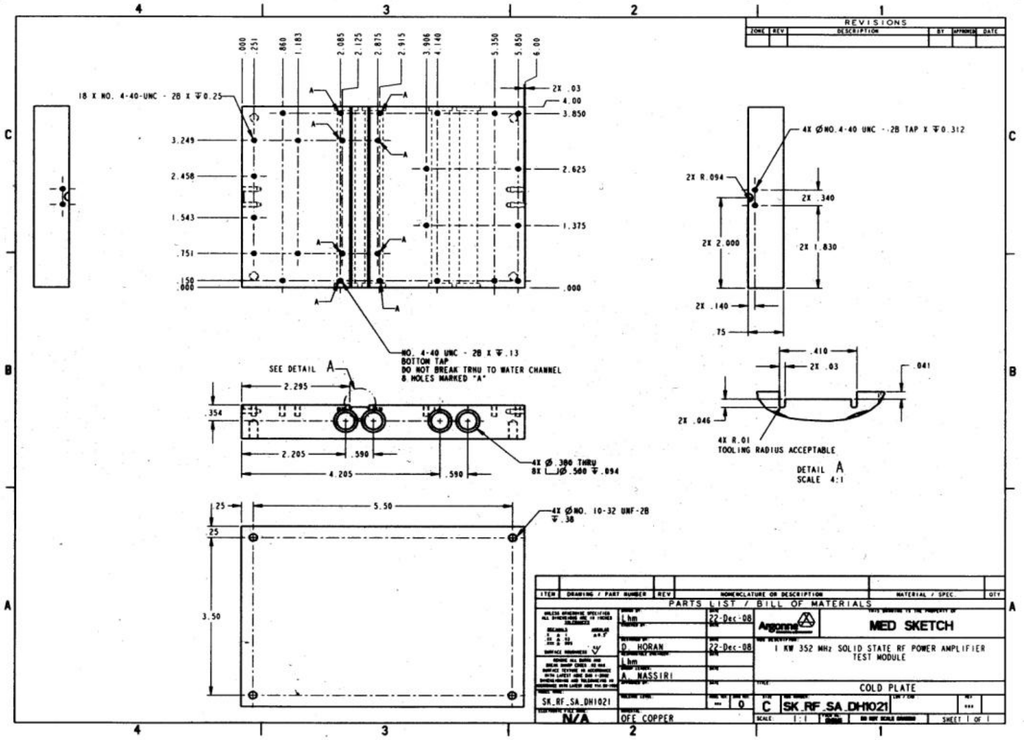


Completed amplifiers

Improved APS Cold Plate Design

- APS developed an improved copper cold plate design to maximize cooling efficiency for the transistor package and output circuit passive components:





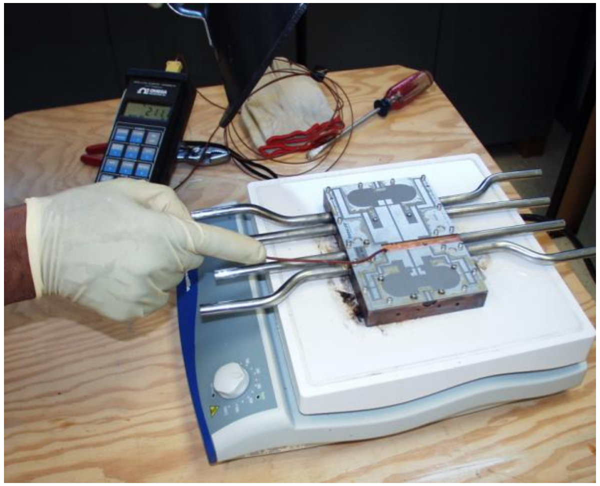
→ “Clamped-part” cold plate has 4-40 threaded holes to attach the transistor to the cold plate

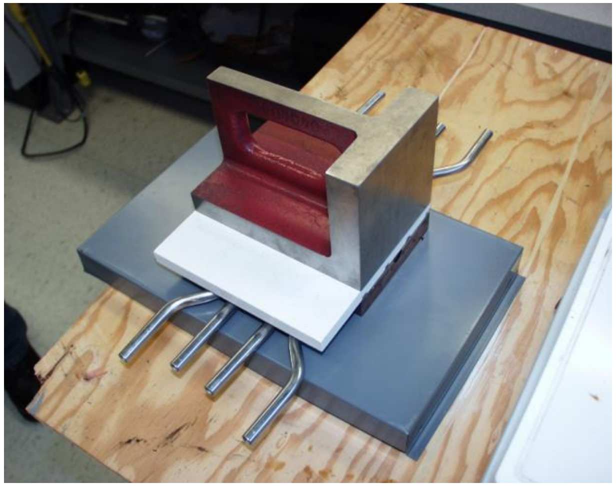
→ “Soldered-part” cold plate has no transistor mounting holes…..transistor is soldered directly onto the cold plate

352-MHz 1kW CW Amplifier Construction

- The cold plates were tinned with 95%Sn/5%Sb solder with a melting point at ~ 240^{o}C

- The circuit board was then soldered to the cold plate and pressed with a weight to insure uniform bonding.
  - → *Insures good thermal and electrical contact between the circuit board and cold plate*
  - → *Uniform good electrical contact on back side of board is necessary for operating stability*



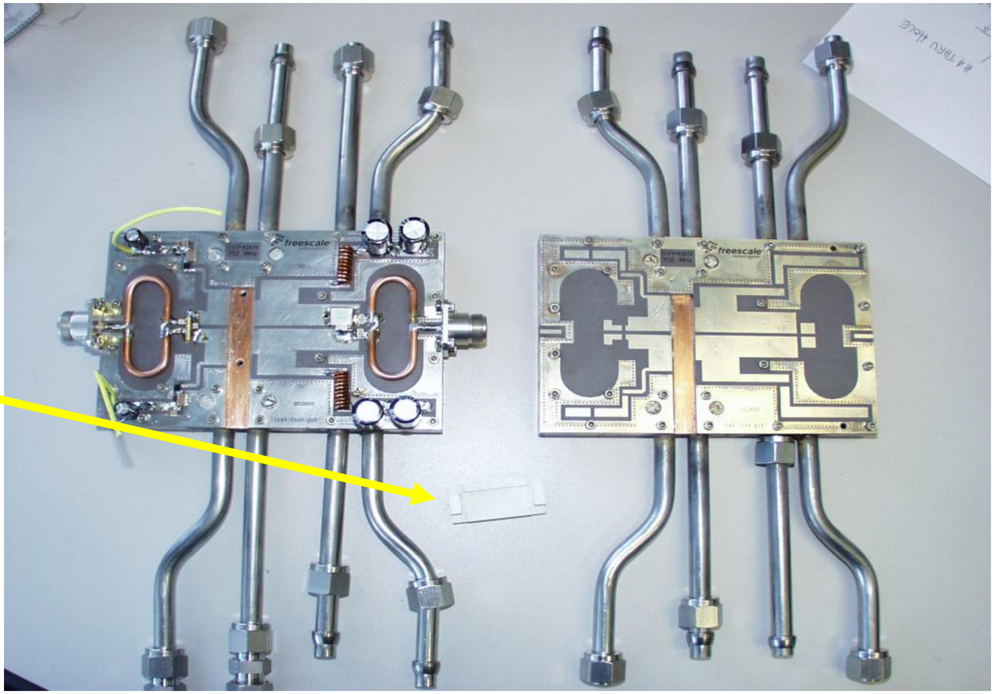


352-MHz 1kW CW Amplifier Construction

- **On the clamped-part amplifier, passive components were soldered to the board foils that were thermally isolated from board ground and cold plate using one (and sometimes two!) 60-watt soldering irons.**

- **On the soldered-part amplifier, the transistor was soldered directly to the cold plate using regular 65%Sn/35%Pb solder with a melting point of approximately 183ºC.**

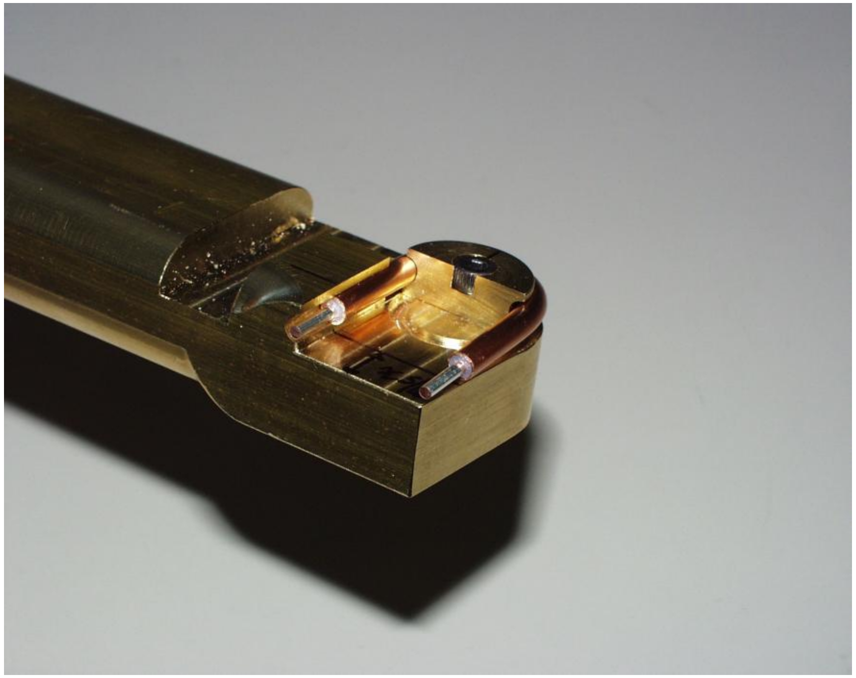
→ ***A hold-down clamp was made from machineable ceramic to apply a small amount of weight to the transistor when it was soldered to the cold plate***



352-MHz 1kW CW Amplifier Construction

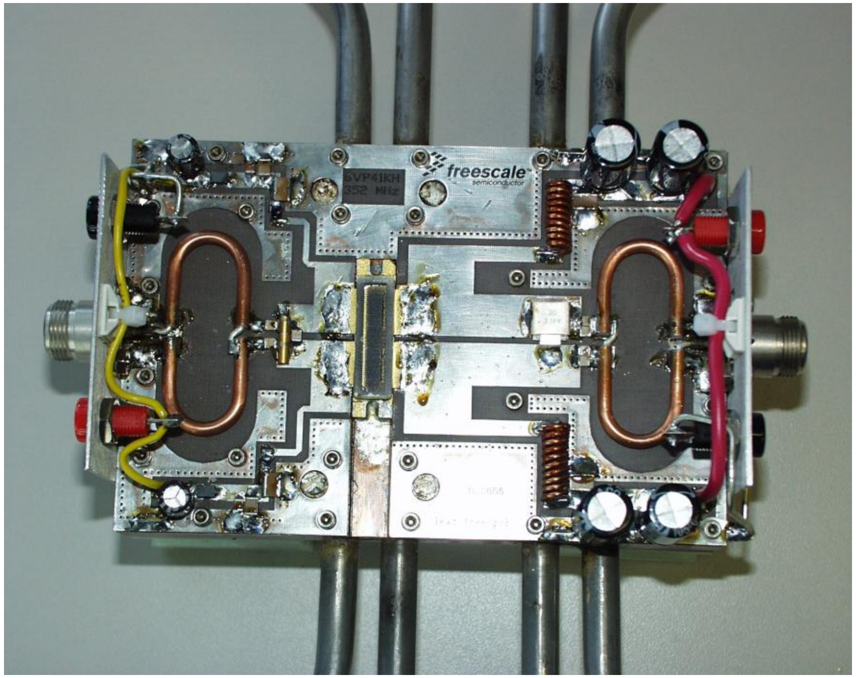
- Special saw (60 teeth/inch, 0.008” thickness) was utilized to cut the 25Ω rigid mini-coax for the input and output baluns

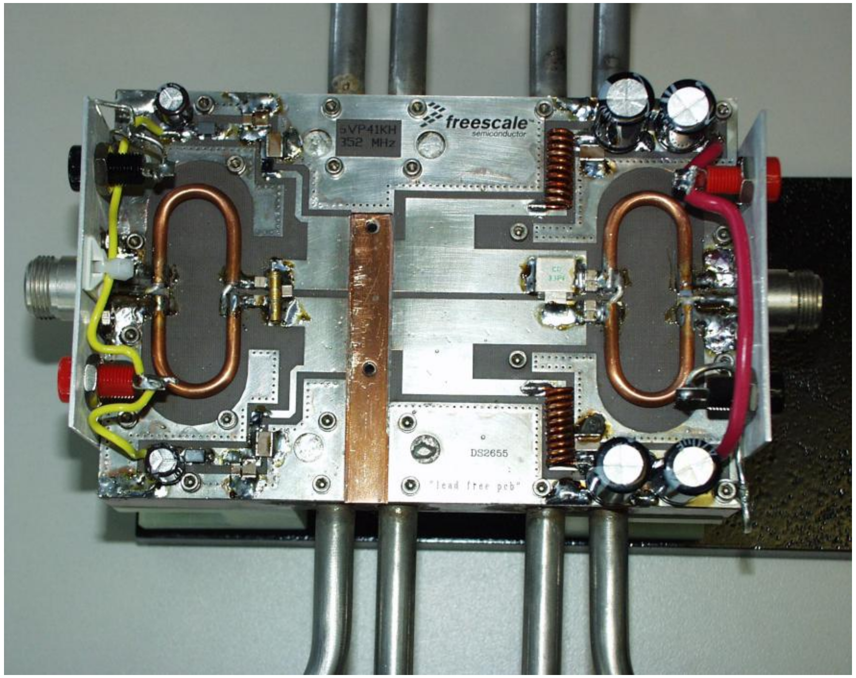
- A bending tool was fabricated to form the coaxial baluns.



352-MHz 1kW CW Amplifier Construction

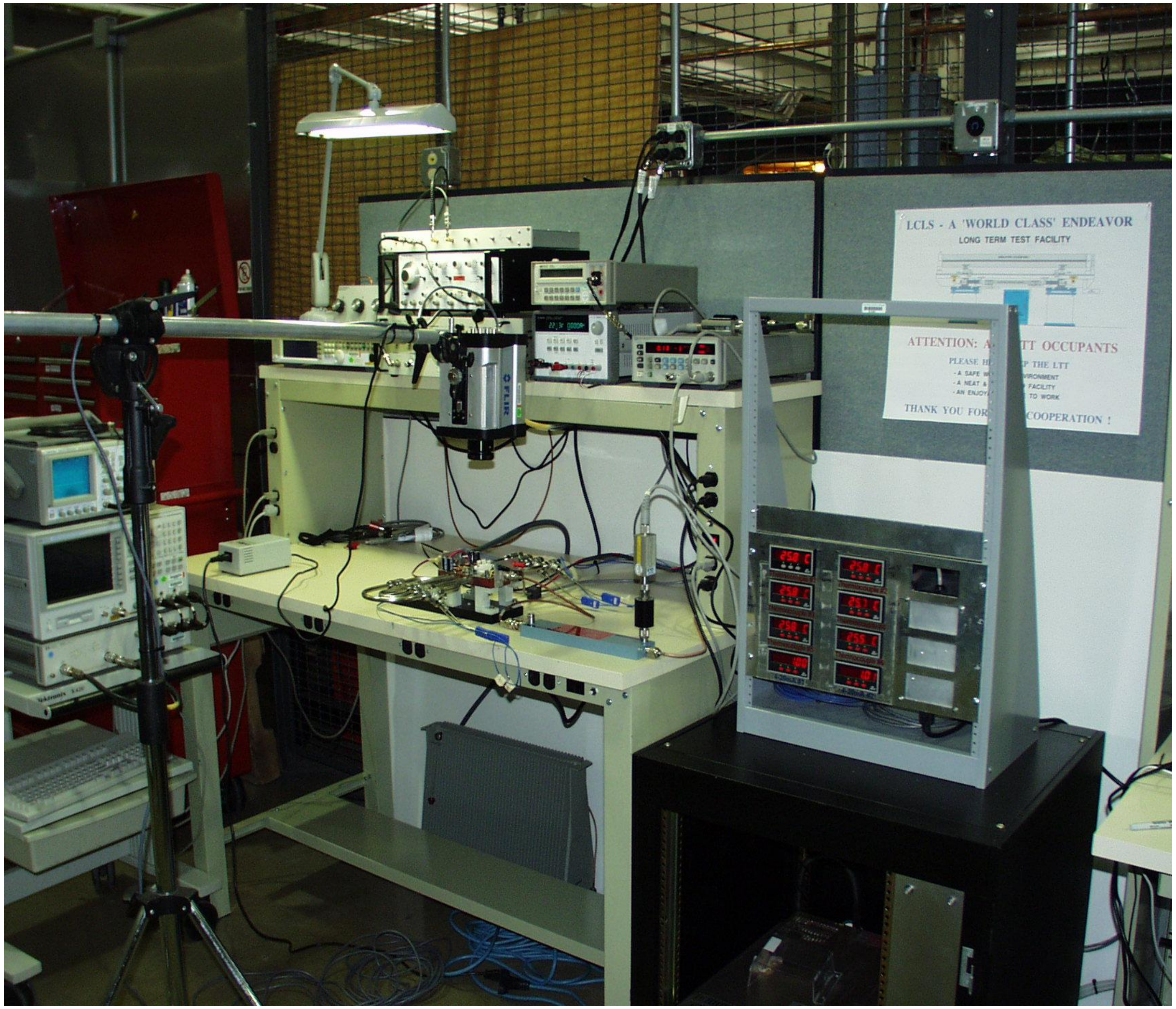
- The remaining assembly was completed by heating the entire assembly to 120ºC on the hot plate and using a 200-watt soldering iron to solder all connections that were thermally bonded to the cold plate.





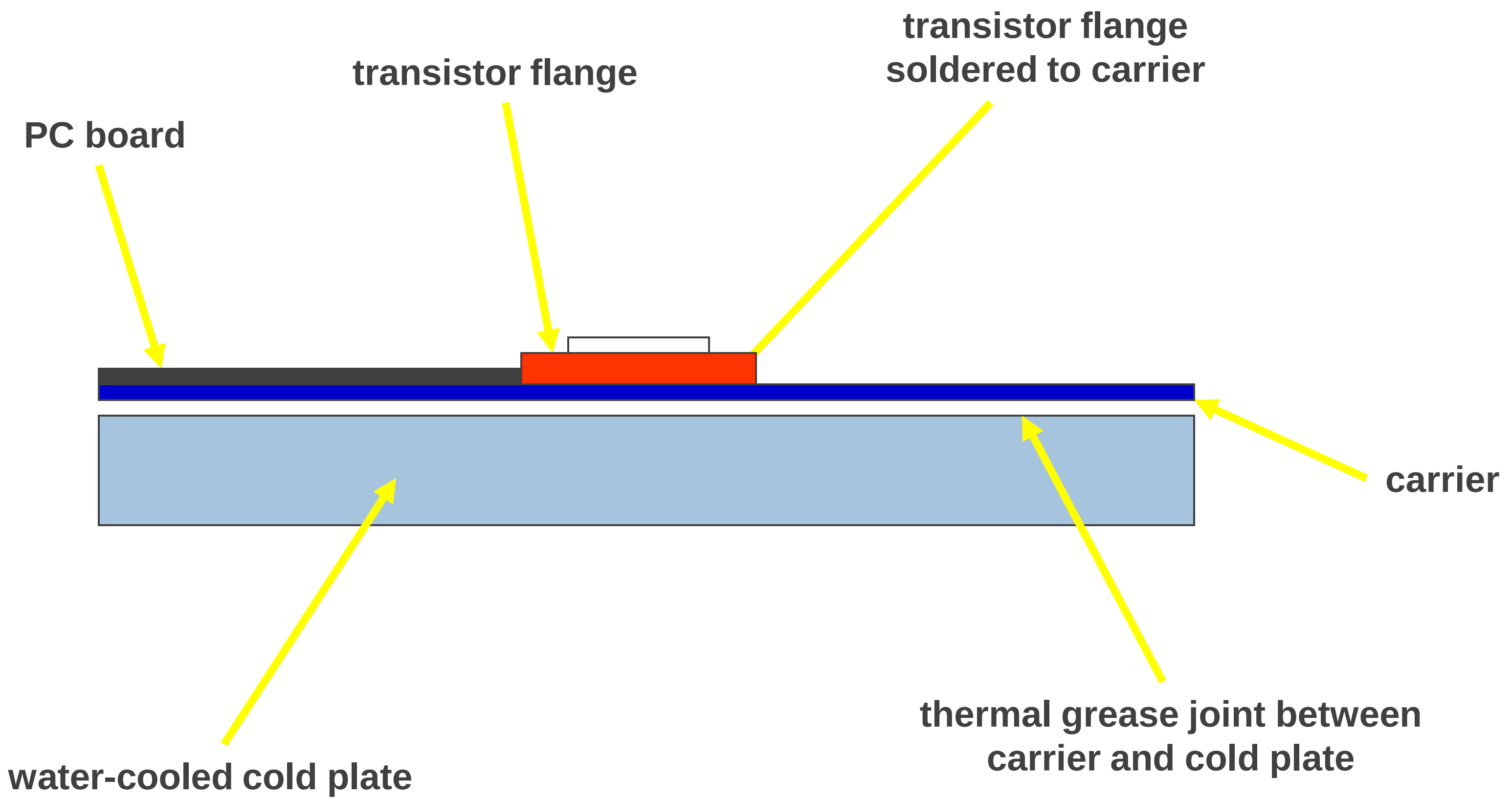
352-MHz 1kW CW Amplifier Test System and Plan

- 75ºF DI water supply for cooling amplifier
- Flow and supply/return temperature monitored on each water circuit
- IR camera for monitoring and recording transistor die temperatures on de-lidded transistors



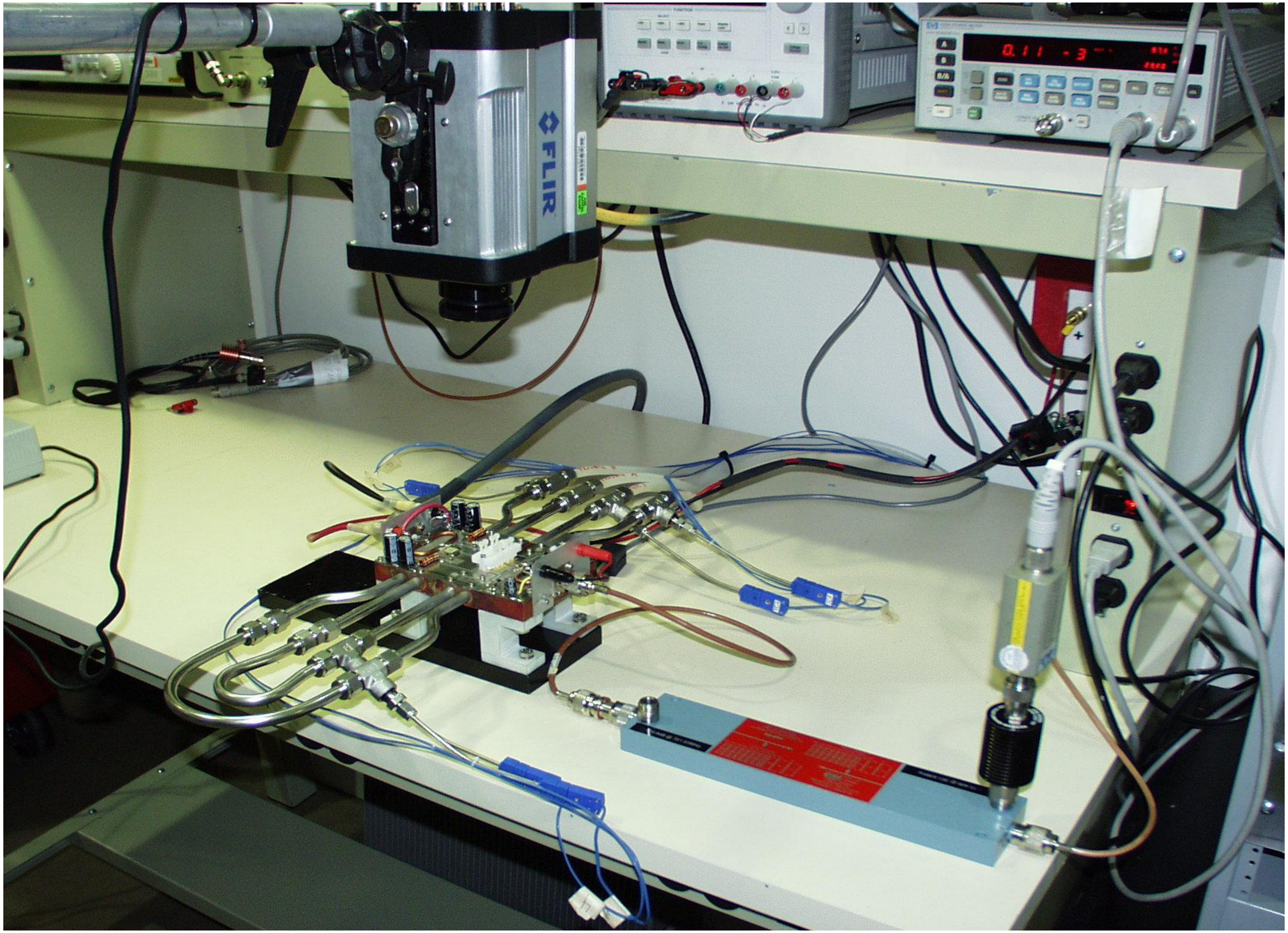
Lessons Learned from Test Results

- **The use of a part "carrier" will make assembly much easier by allowing normal soldering techniques**



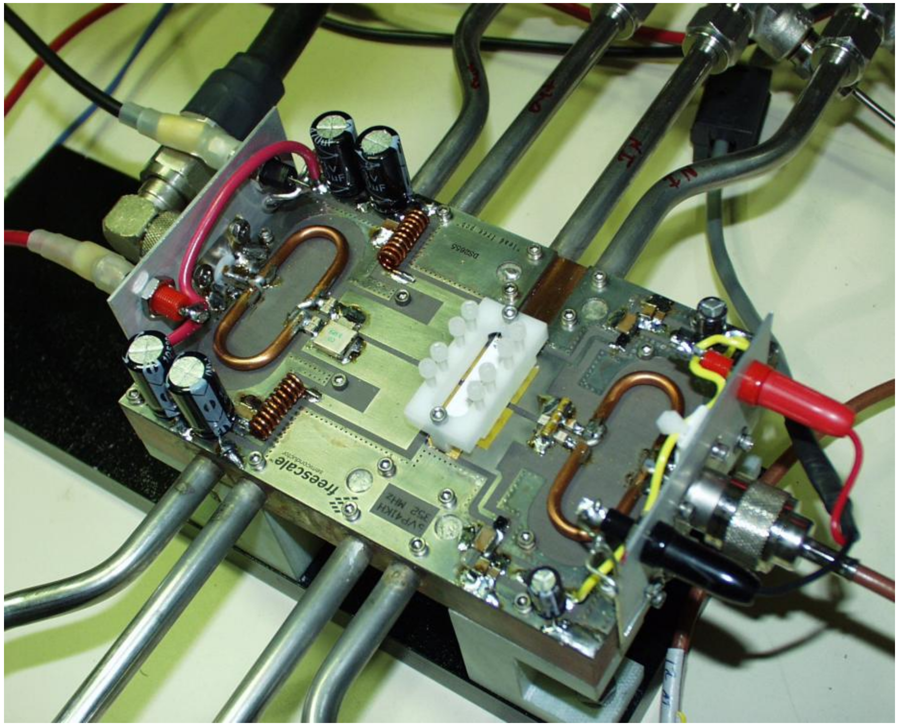
Carrier thickness of 4-6 mm will provide adequate thermal performance

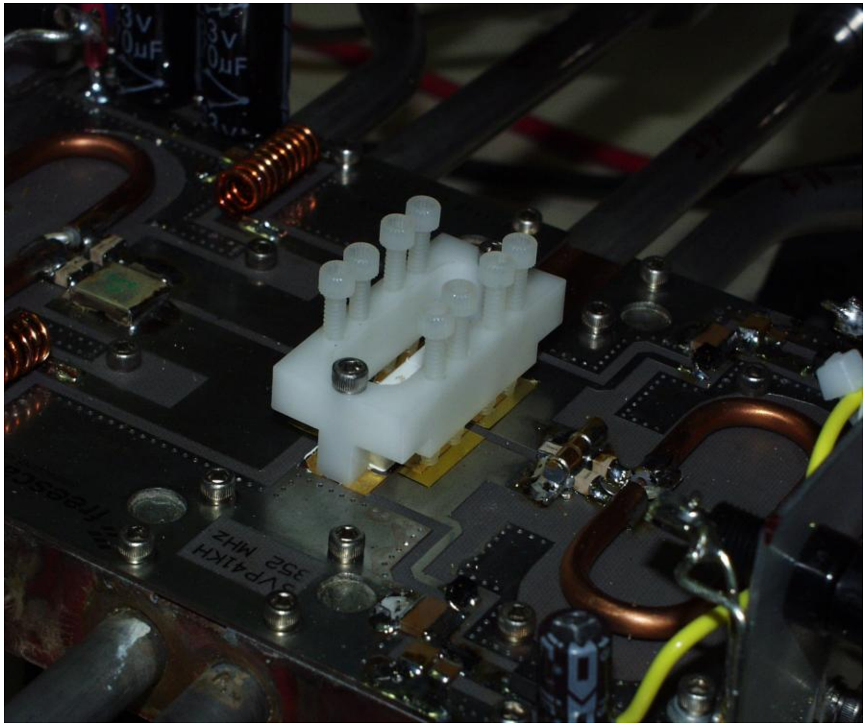
352-MHz 1kW CW Amplifier Test System and Plan



352-MHz 1kW CW Amplifier Test System and Plan

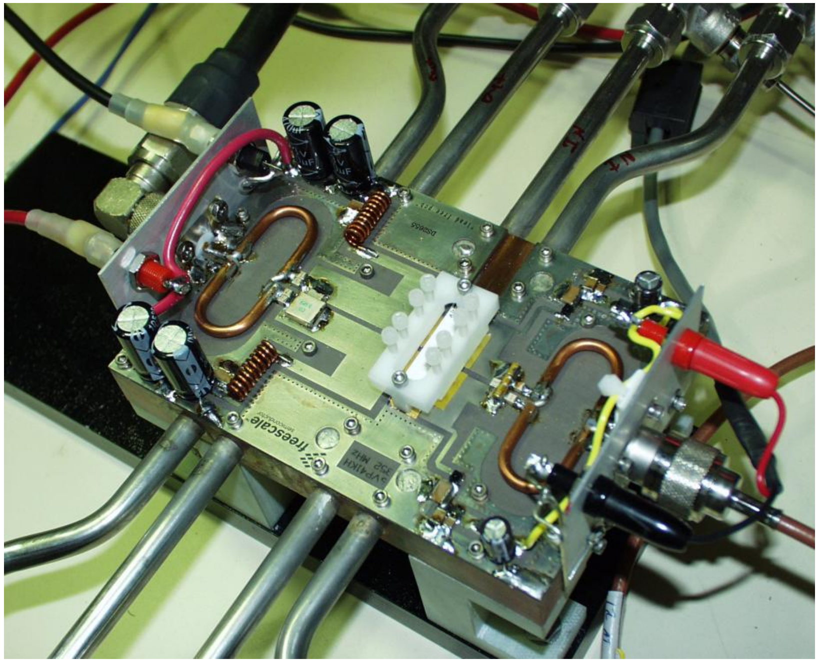
- The "clamped-part" amplifier uses a delrin clamp to mount the transistor to the cold plate, using a screw torque of 5 in-lbs.
- The delrin clamp holds transistor leads to board allowing for removal without damaging board.





352-MHz 1kW CW "Clamped Part" Amplifier Test Results

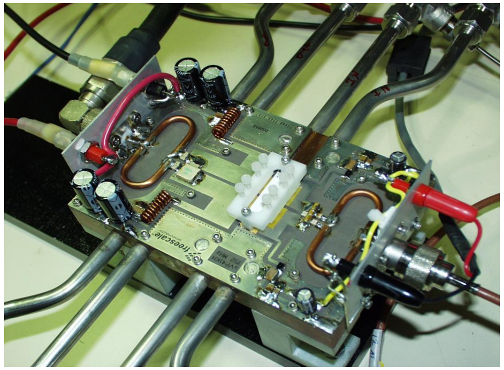
- **Clamped-part amplifier test results:**
  - → Vd = 49.46V
  - → Id = 29.06A
  - → Idq ≈ 150mA
  - → Pdc input = 1437.3 watts
  - → Efficiency = 63.2%
  - → RF output ≈ 909 watts (derived from water calorimetric power calculations)
  - → RF input = 8.53 watts
  - →Input return loss = 10.3dB
  - →RF gain ≈ 20.2dB
  - →Water calorimetric power = 528 watts

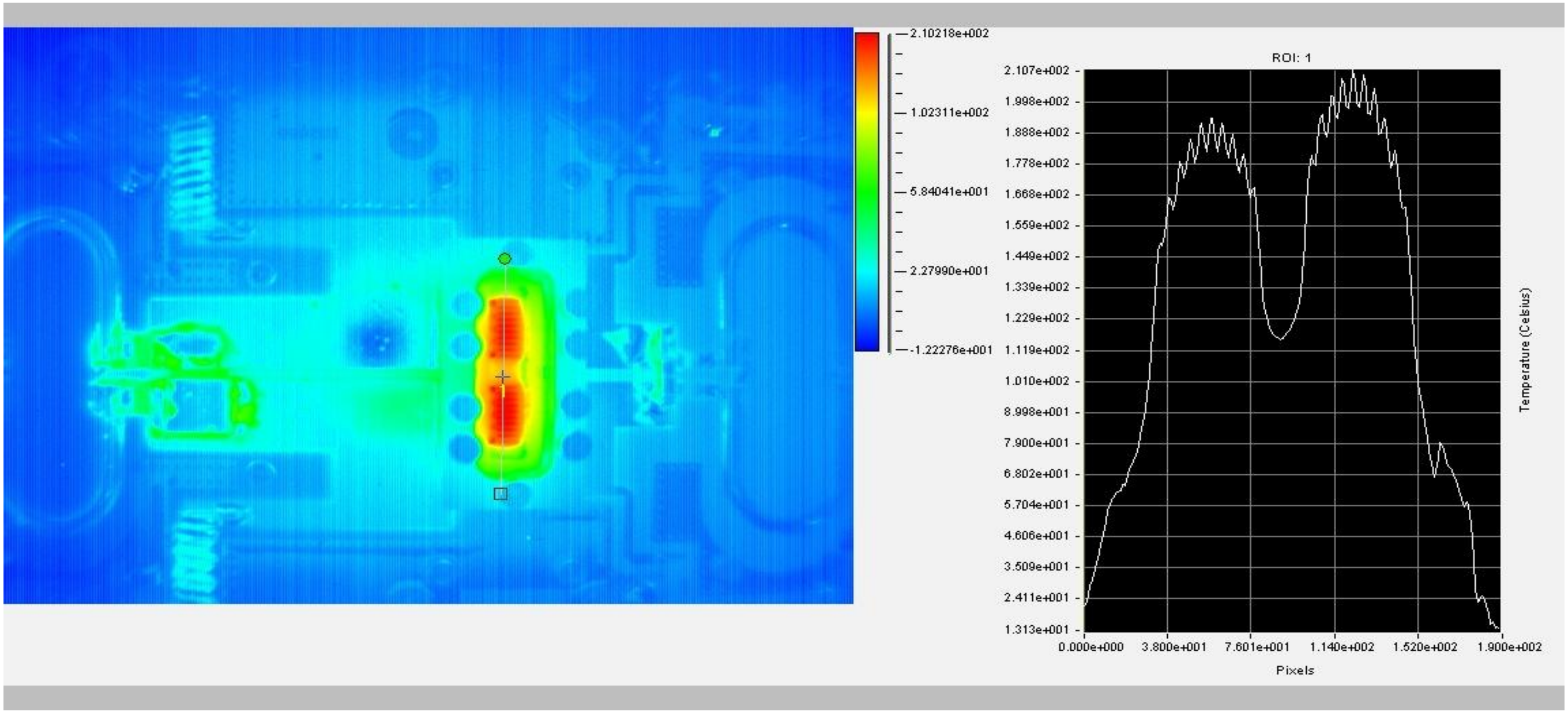


Initial efficiency was abnormally high (69.5%), so rf power meter readout at 1kW was suspect……….rf power was derived from power dissipation in water circuits

352-MHz 1kW CW “Clamped Part” Amplifier Test Results

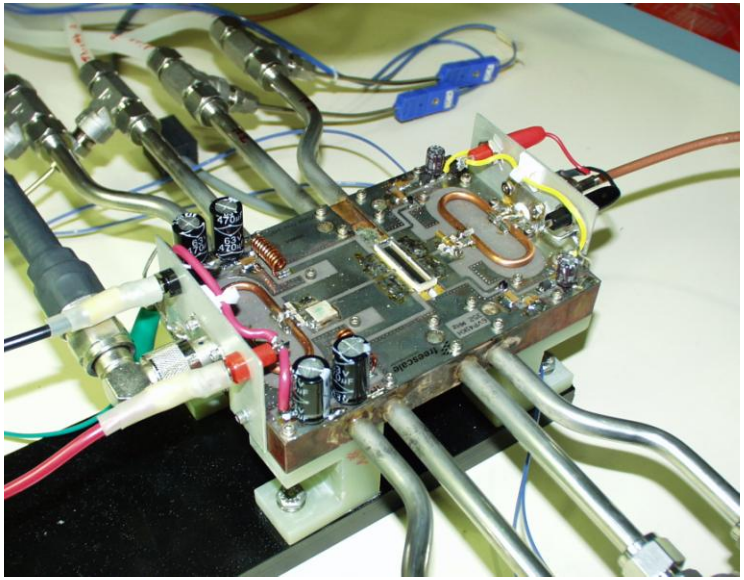
- Maximum die temperature was 210ºC at ~ 909 watts output – *excessive for reasonable device MTTF*
- *Test results agree with Freescale predictions for a clamped part*

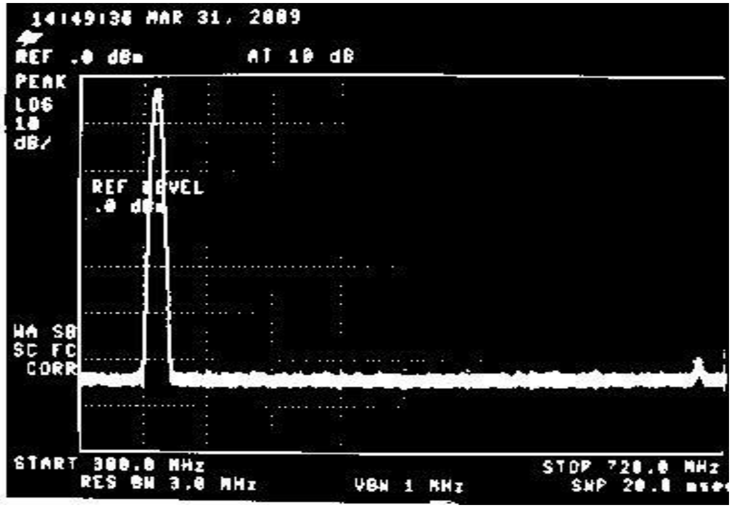




352-MHz 1kW CW "Soldered Part" Amplifier Test Results

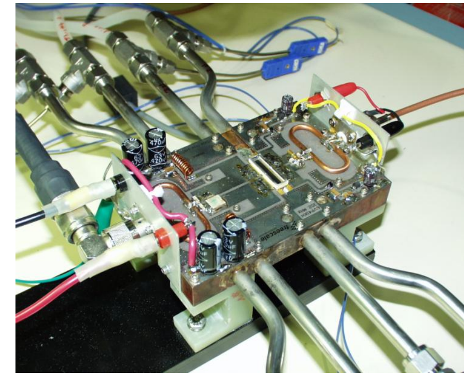
- **Soldered-part amplifier test results:**
  - → Vd = 49.26V
  - → Id = 30.65A
  - → Idq ≈ 150mA
  - → Pdc input = 1509.82 watts
  - → Efficiency = 66.2%
  - → RF output = 1000 watts
  - → RF input = 8.32 watts
  - → Input return loss = 10.07dB
  - → RF gain = 20.79dB
  - → Water calorimetric power = 572.8 watts

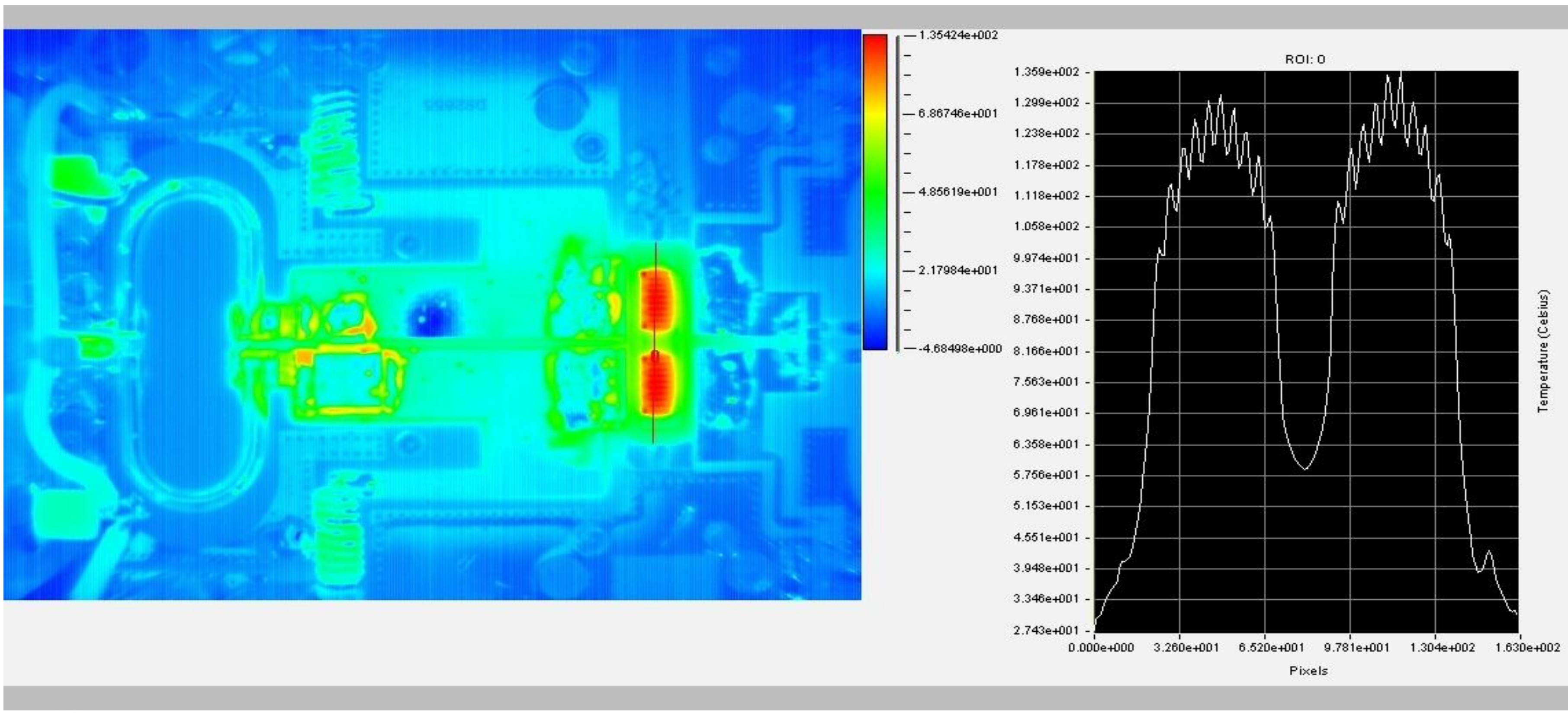




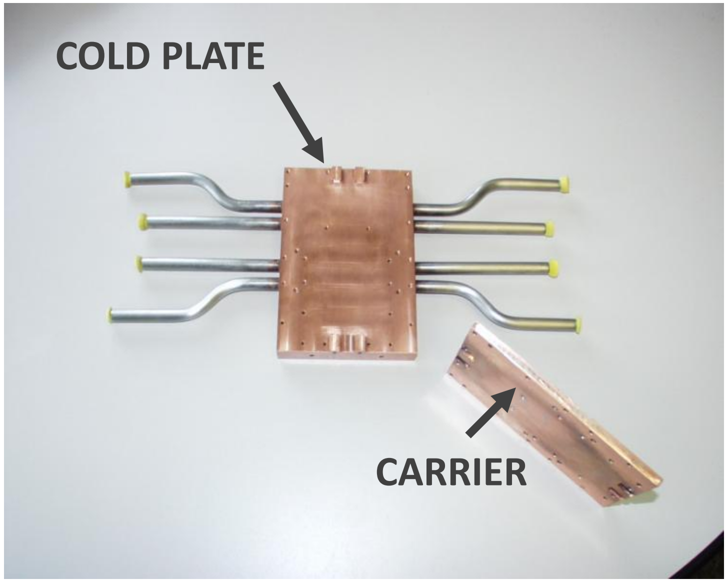
352-MHz 1kW CW "Soldered Part" Amplifier Test Results

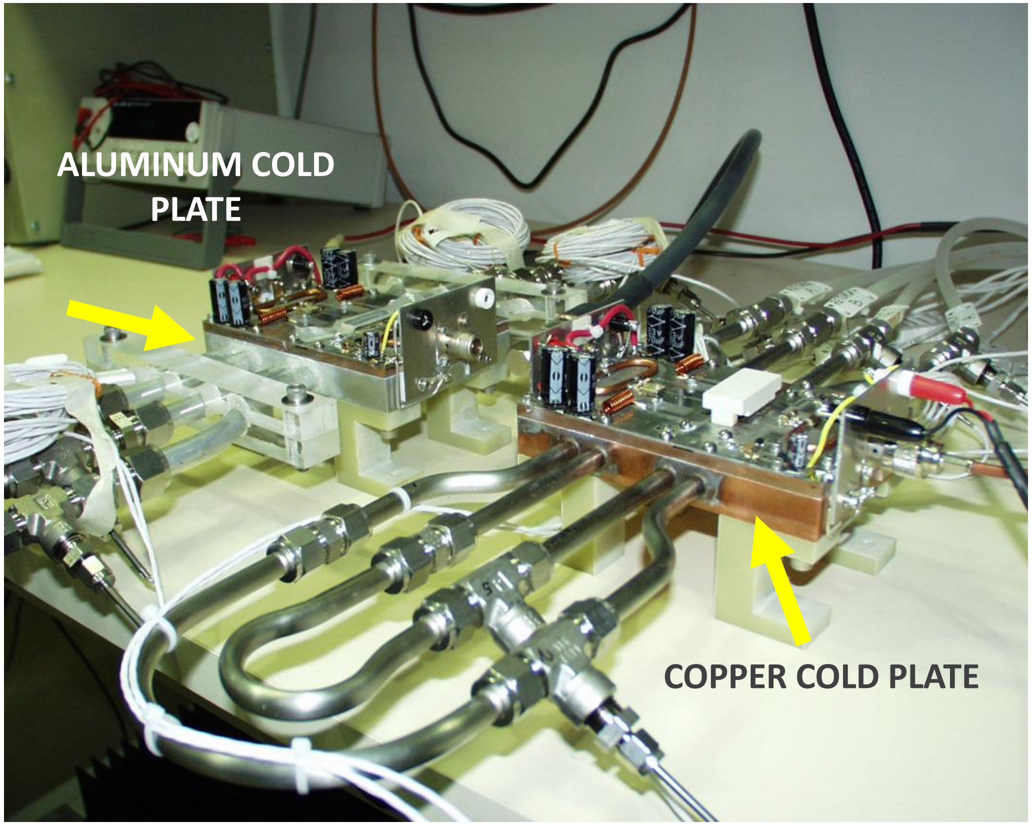
- **Maximum die temperature was 136ºC at 1kW output – *translates to a device MTTF of ~ 9E+6 hours.***
- **Temperature on top of flange between dies ~ 58ºC**
- ***As expected, the soldered-part construction technique offers more efficient cooling of device.***





Construction of “Carrier-Cold Plate” Amplifiers

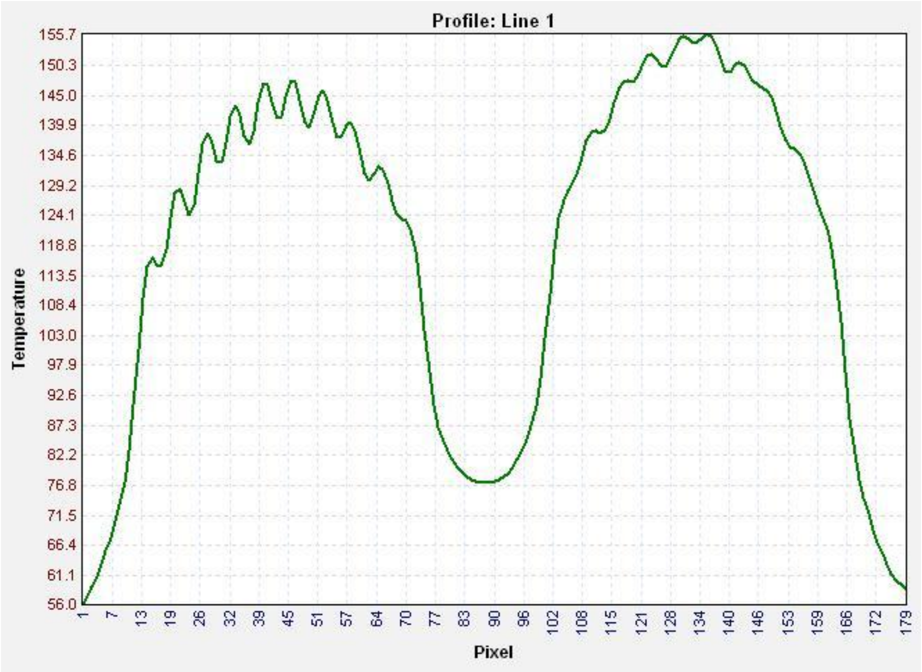


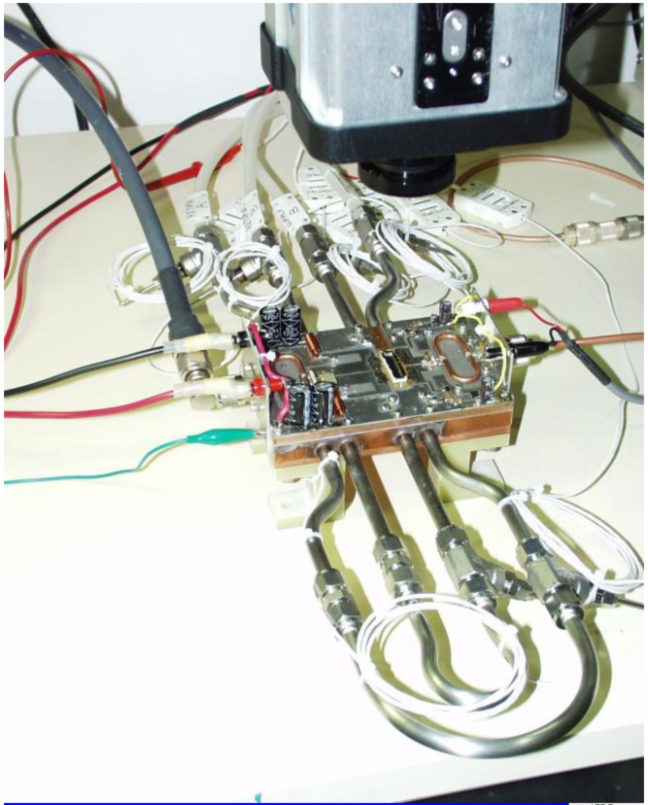


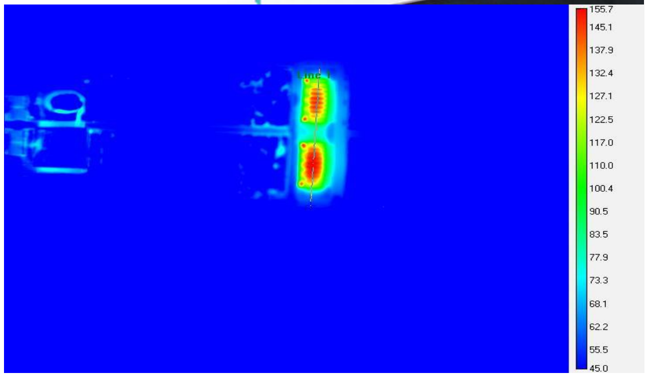
- **Amplifier circuit board soldered to 0.25” carrier**
- **Carrier attached to cold plate by screws, using thermal grease for heat transfer**
- **Aluminum and copper cold plate built and tested**

Testing of Copper Cold Plate Amplifier

- **Maximum die temperature at 1,012 watts output was 155.7 C**
- **69.6% efficiency**

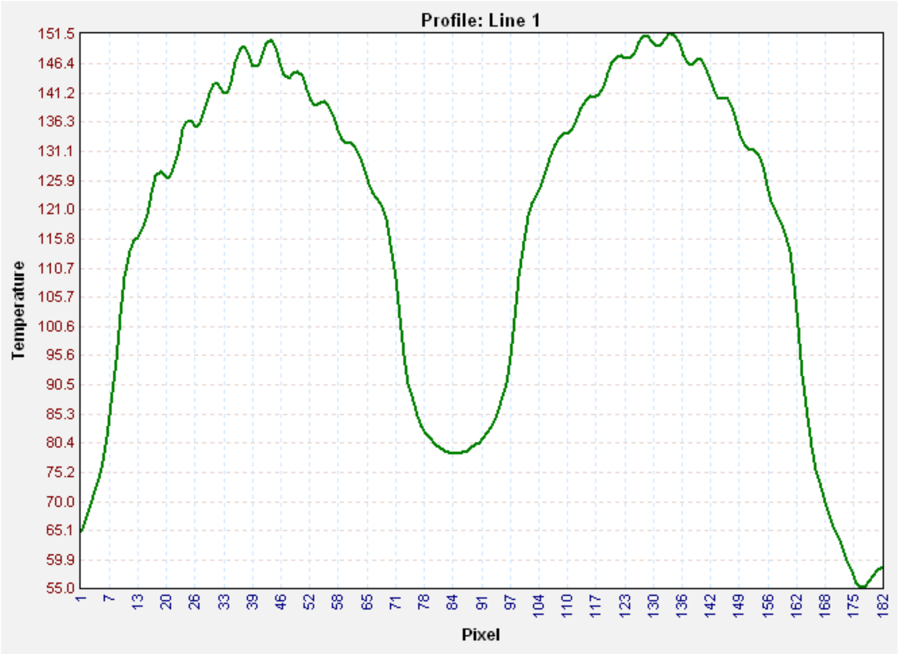


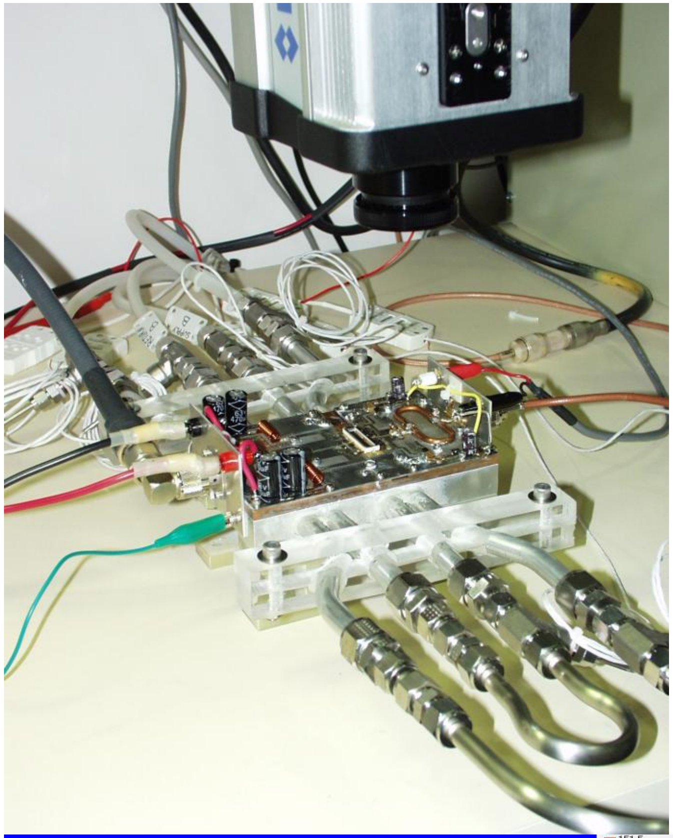


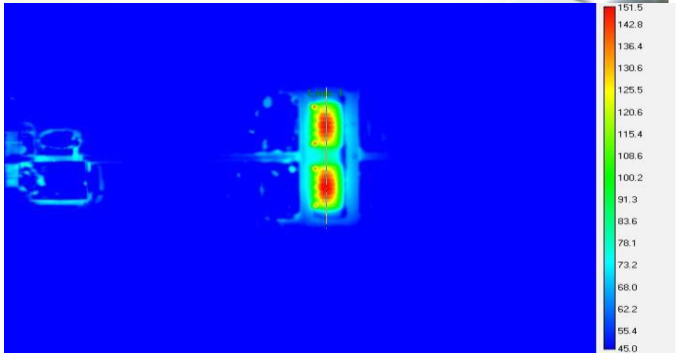


Testing of Aluminum Cold Plate Amplifier

- **Maximum die temperature at 1,010 watts output was 151.5°C**
- **69.6% efficiency**

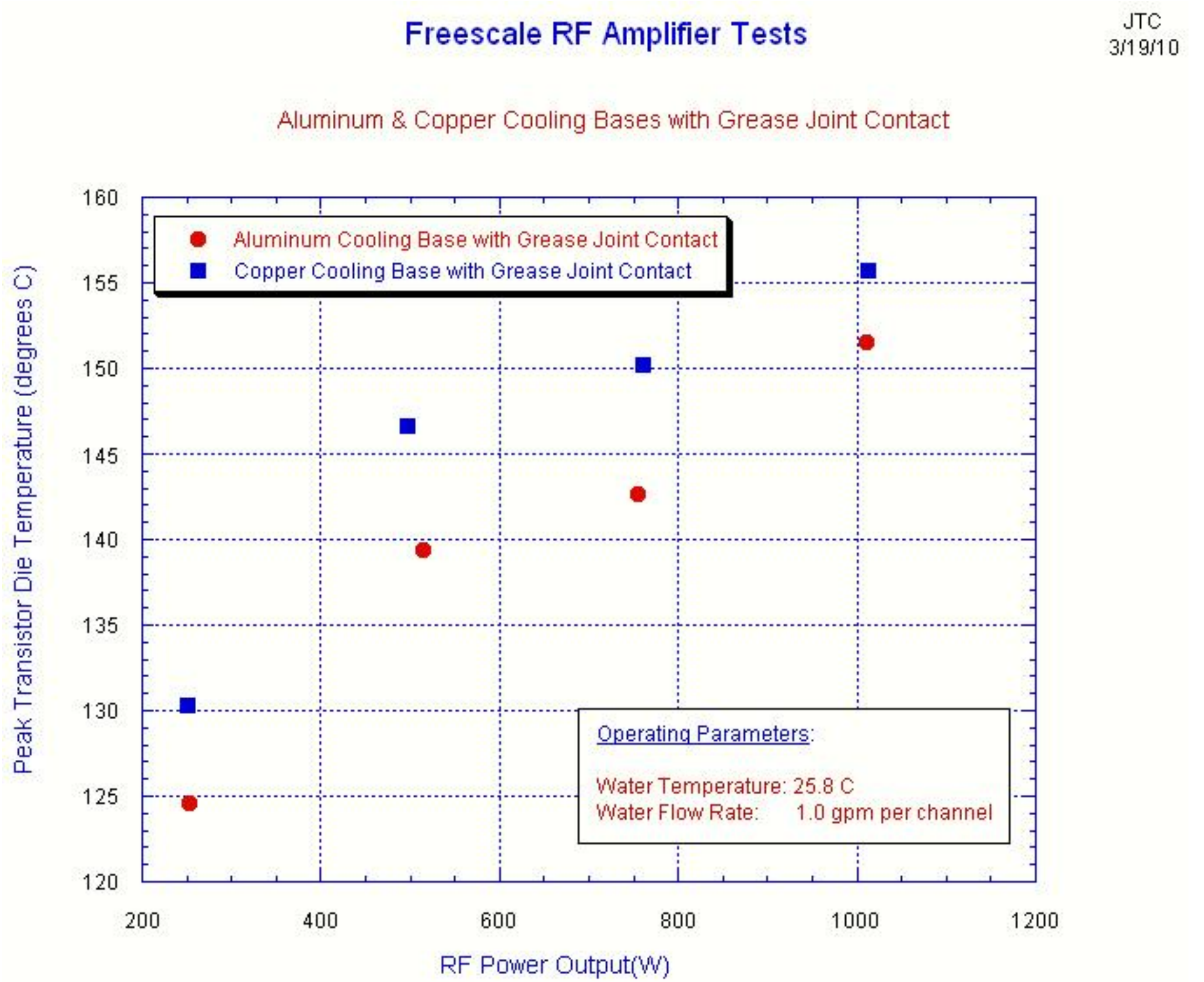






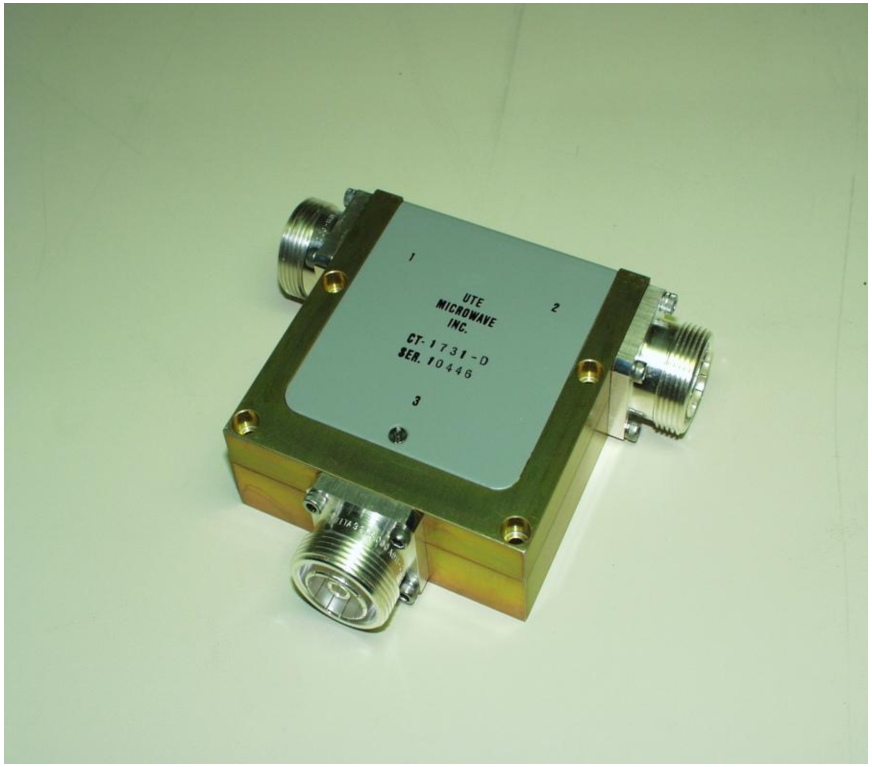
Thermal Performance of Aluminum and Copper Cold Plates

- **Aluminum cold plate seems to perform better**
- **Thermal analysis by Jeffery Collins, ANL**



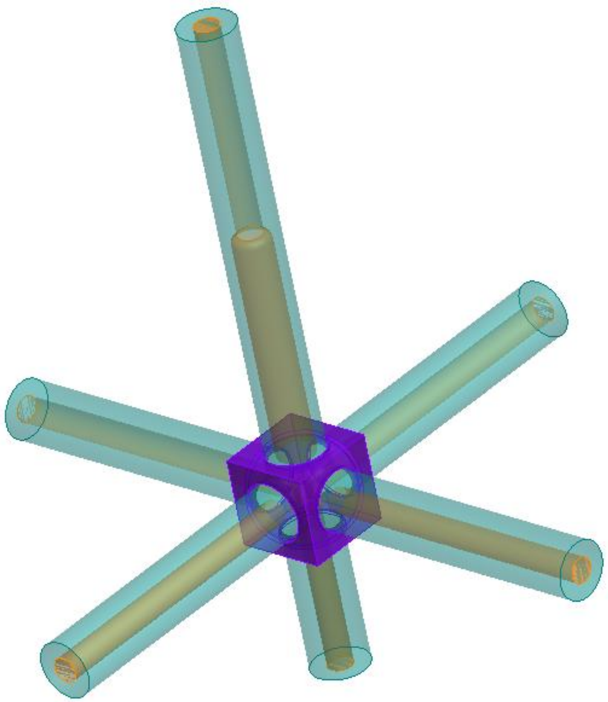
1kW Circulator Procurement and Test

- Four circulators were purchased from UTE Microwave
- Will be used to provide amplifier isolation on the ¼-wave combiner
- One circulator has been tested under power and met advertised specifications at 1kW power level

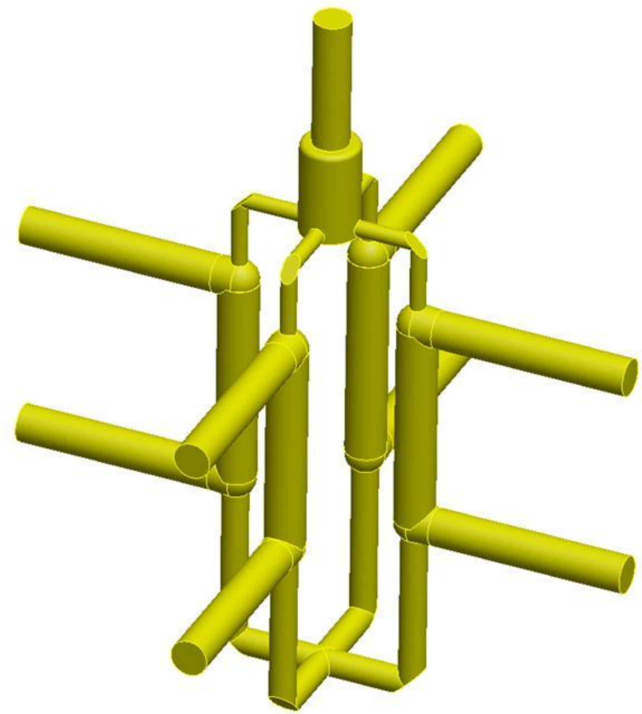


Design of Quarter-Wave 4-Way Combiner

- **Two combiner types were chosen for initial tests:**

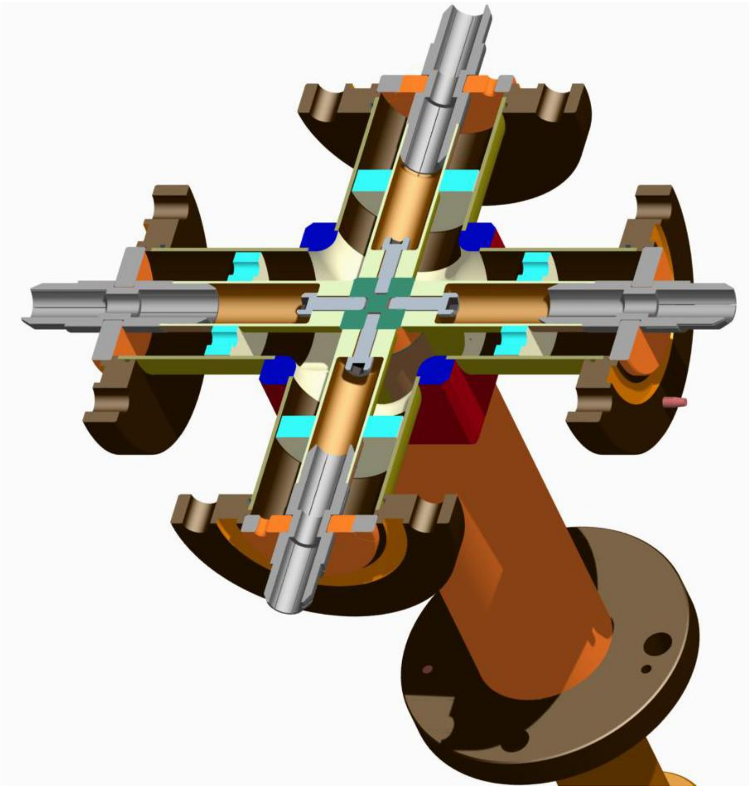


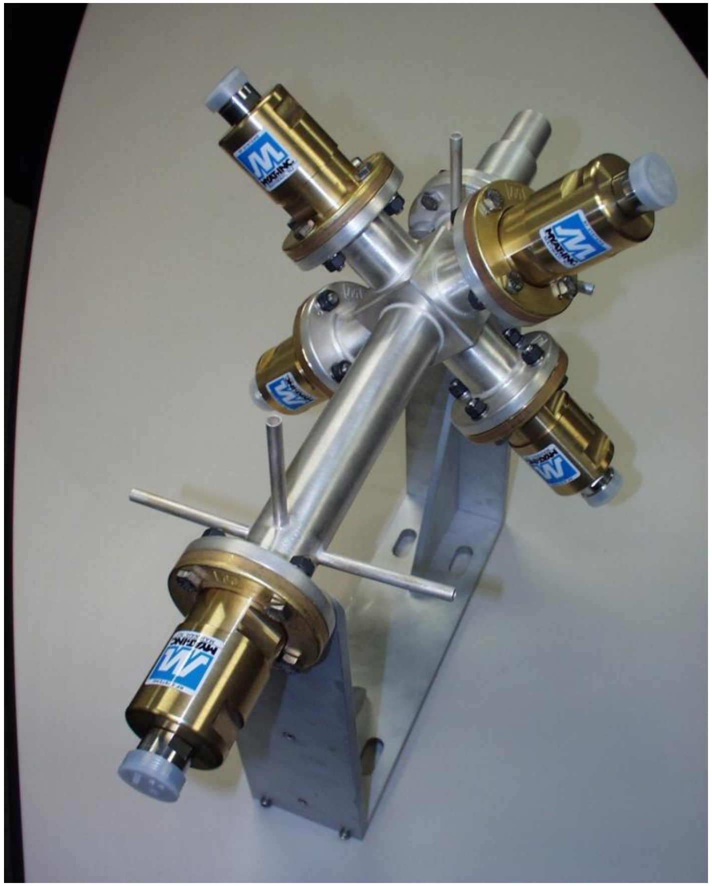
Standard quarter-wave coaxial combiner



Gysel Combiner

Design of Prototype Quarter-Wave 4-Way Combiner





- **Constructed with 1-5/8” EIA standard coaxial components**
- **Utilizes sliding shorting plunger for tuning**

Conclusions From Initial Test Results

- The MRF6VP41KHR6 device is a possible candidate for the APS solid-state amplifier project.

- The existing APS 90ºF de-ionized water system could be used to cool the amplifiers.

- Carrier + Cold Plate construction has minimal thermal impact

- Passive components and circuit board must be made more robust for continuous CW output at 1kW.

Plan for Remainder of FY10

1. Investigate the possibility of maintaining at least 60% efficiency over 6dB range of output power by varying drain voltage:
   → **Test carrier amplifiers for efficiency at varying drain voltages**
   ………*Look into possible MRF6VP41KHR6 destructive parasitic oscillation?*

2. Demonstrate successful combined-amplifier operation at 4kW output and evaluate the system on the following criteria:
   → **Overall efficiency, ac line to rf output**
   → **Performance of combiner compared to EM model**

3. Begin rf circuit design for APS 352-MHz pre-driver, driver, and 1kW amplifier boards:
   → **Investigate NXP BLF578 transistor?**

4. Build and test 4-way Gysel combiner

Acknowledgments

The efforts and contributions of the following colleagues made this work possible:

→ Branislav Brajuskovic – Mechanical Engineer, ANL

→ Jeffery Collins – Mechanical Engineer, ANL

→ Leonard Morrison – Mechanical Engineer, ANL

→ Geoff Waldschmidt – Electrical Engineer, ANL