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

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Fermilab Project X Collaboration Meeting

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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*

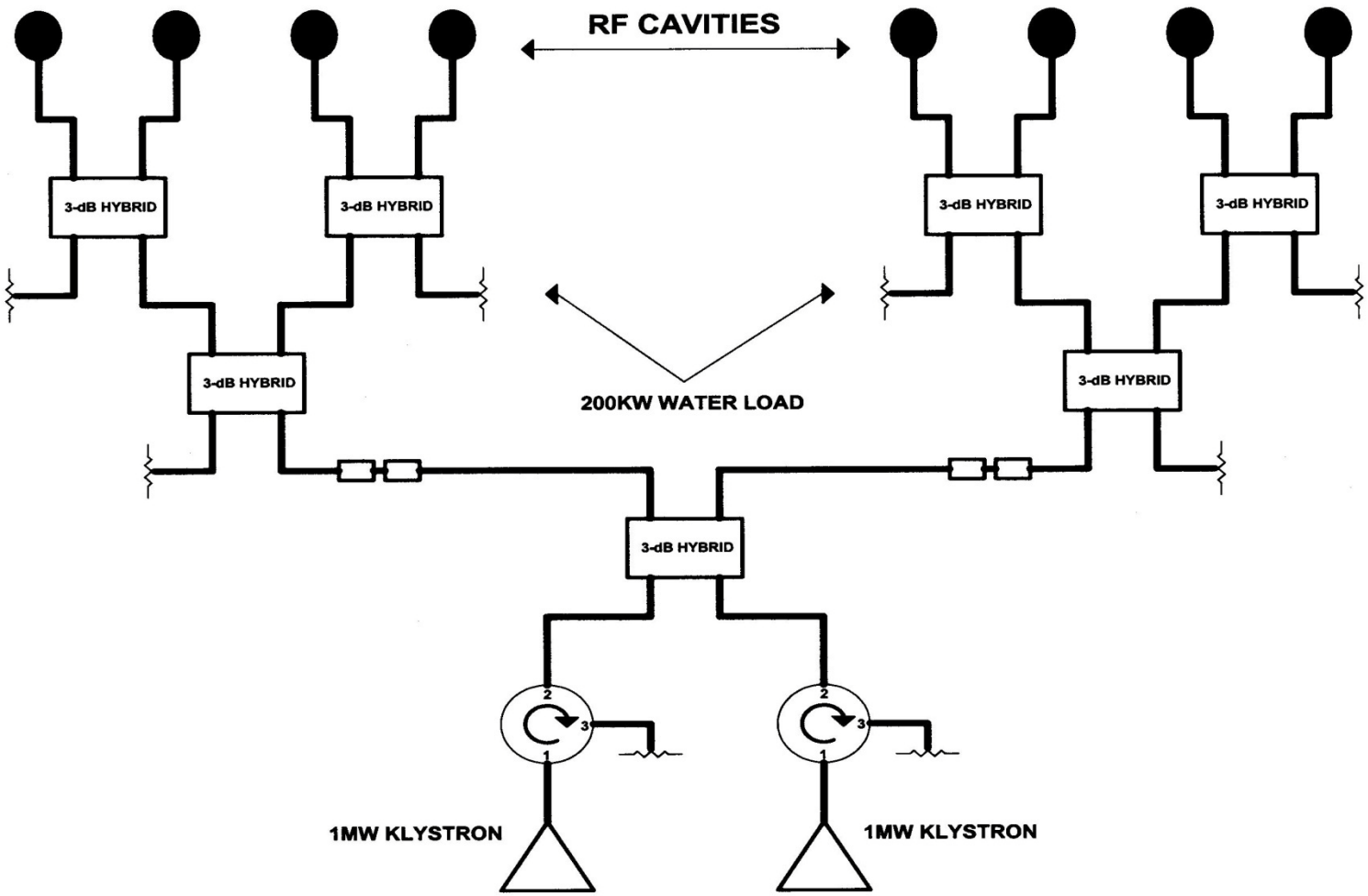
→ *Typical rf output power for storage ring rf stations is ~ 600-700kW CW at this time*

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

Typical rf system downtime is ~ 0.05 - 0.2%

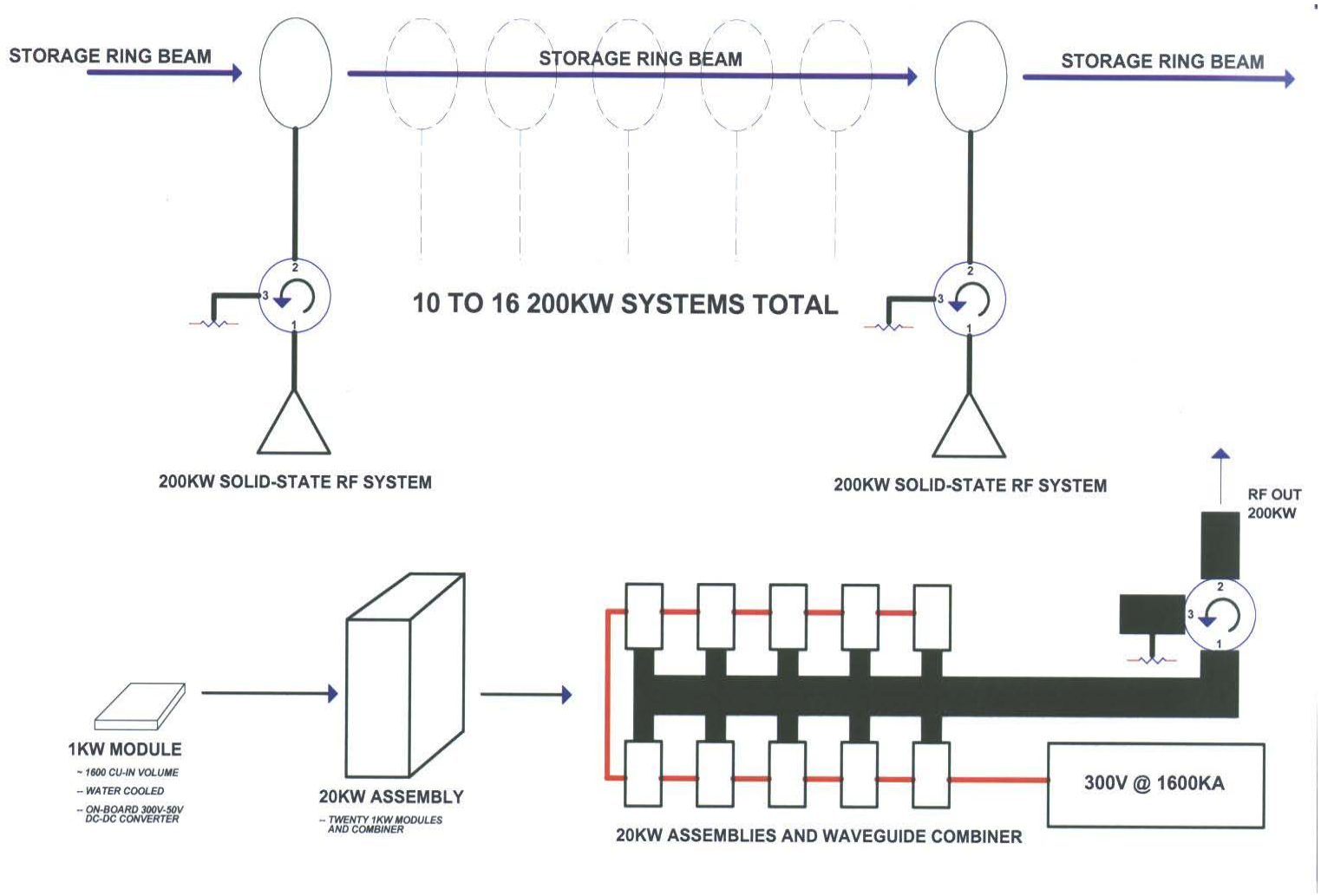
Present 350-MHz RF System Devices and Configuration

- 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:**

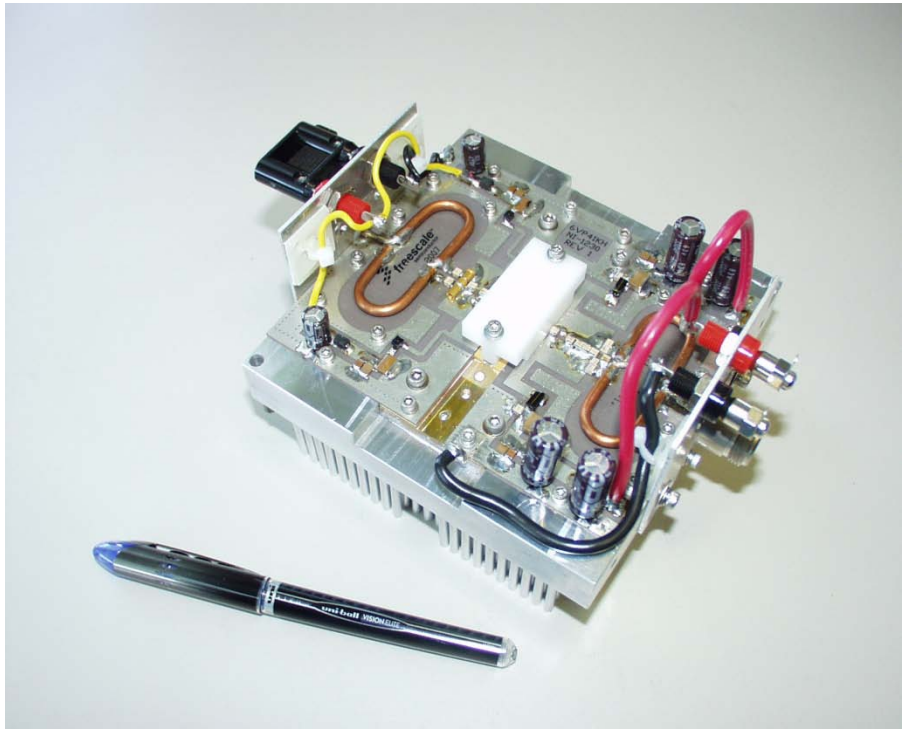
  → Two years, FY09-FY10

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……

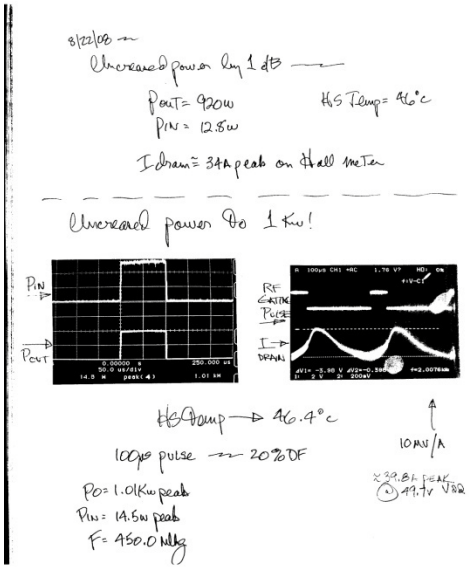


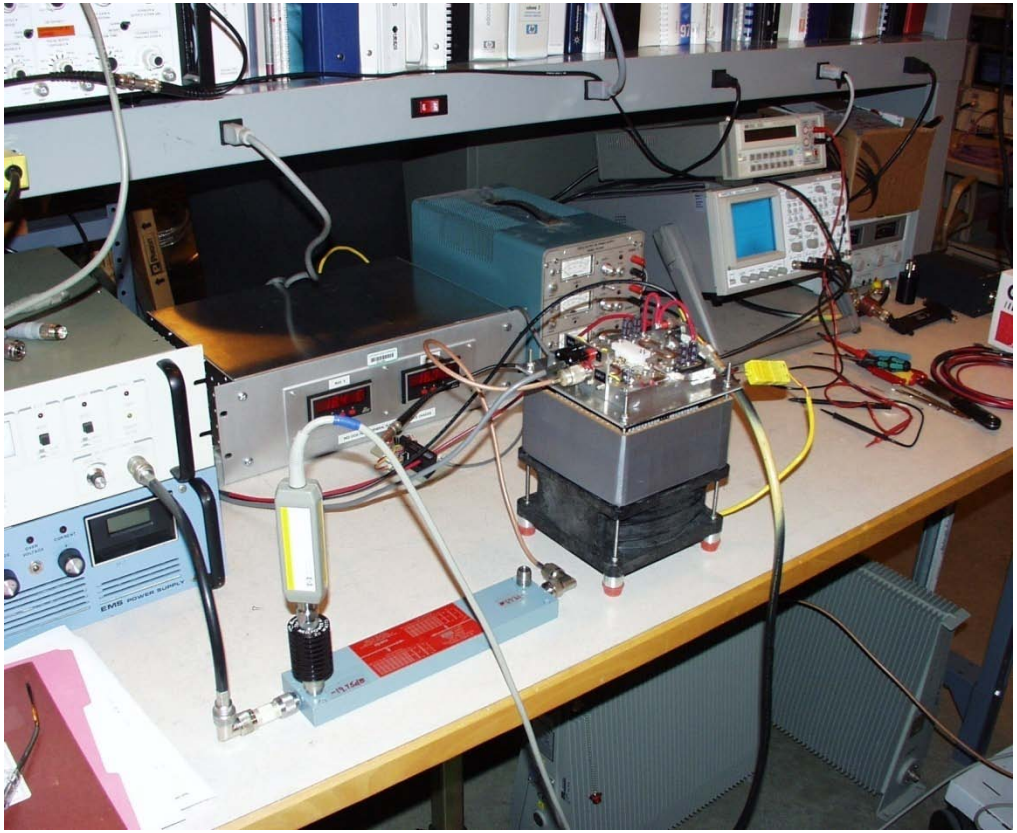
- We obtained a 450-MHz evaluation board kit from Freescale and tested it at rated power.

Initial Tests of the Freescale MRF6VP41KHR6 Device

- The evaluation board produced 1kW peak power at 450MHz, 100us, 20%DF with no problems

- Pulse width increased to 50% DF and the amplifier survived.....
  → *but passive components in output network were overheating.*

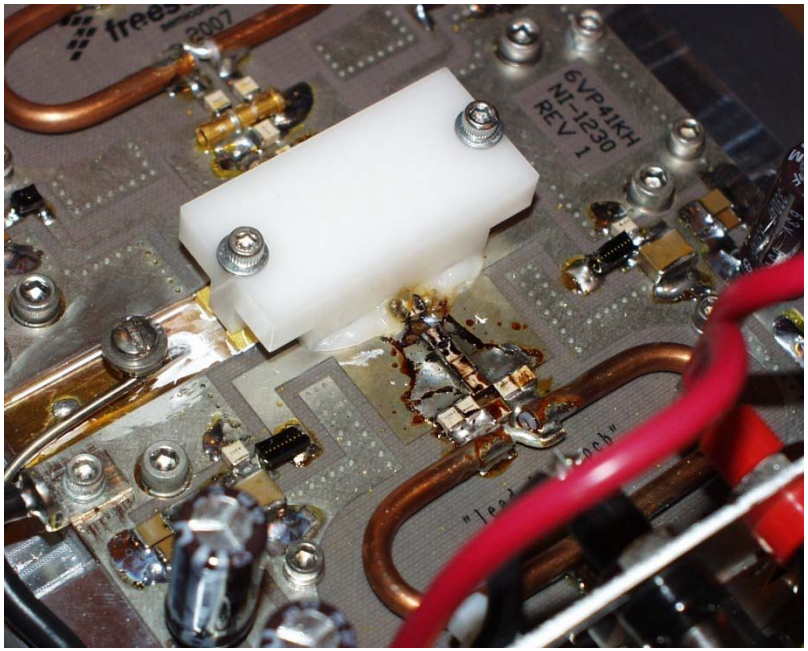


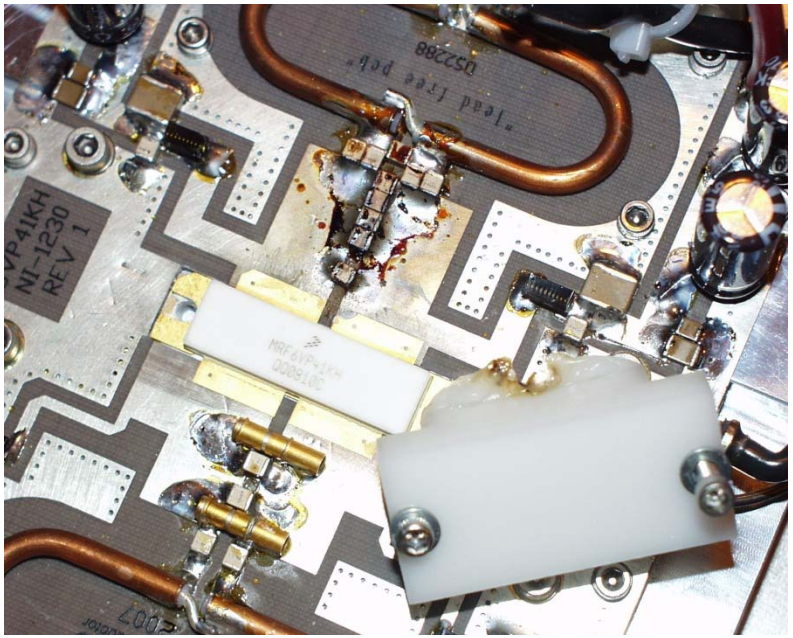


Amplifier test setup showing
Forced-air cooling of "pin fin" heat sink

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.*





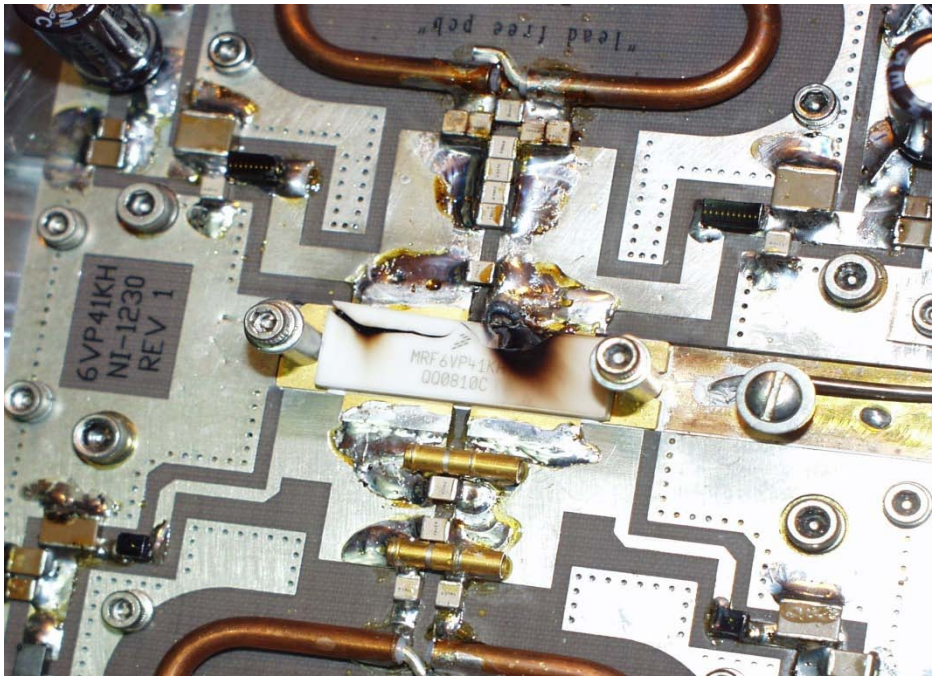
Initial Tests of the Freescale MRF6VP41KHR6 Device

- 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?***

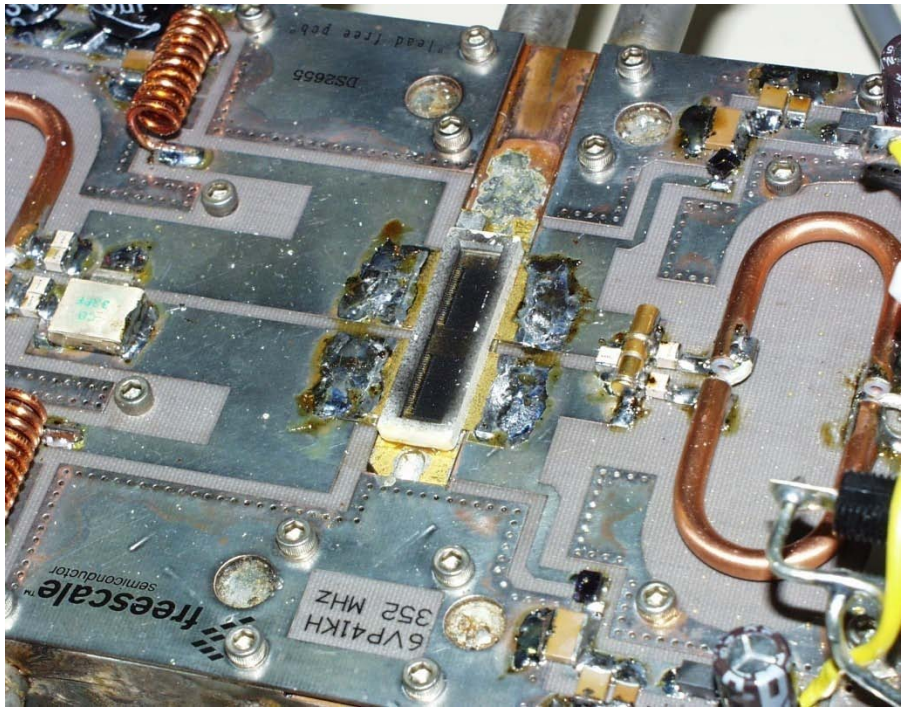


Initial Tests of the Freescale MRF6VP41KHR6 Device

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

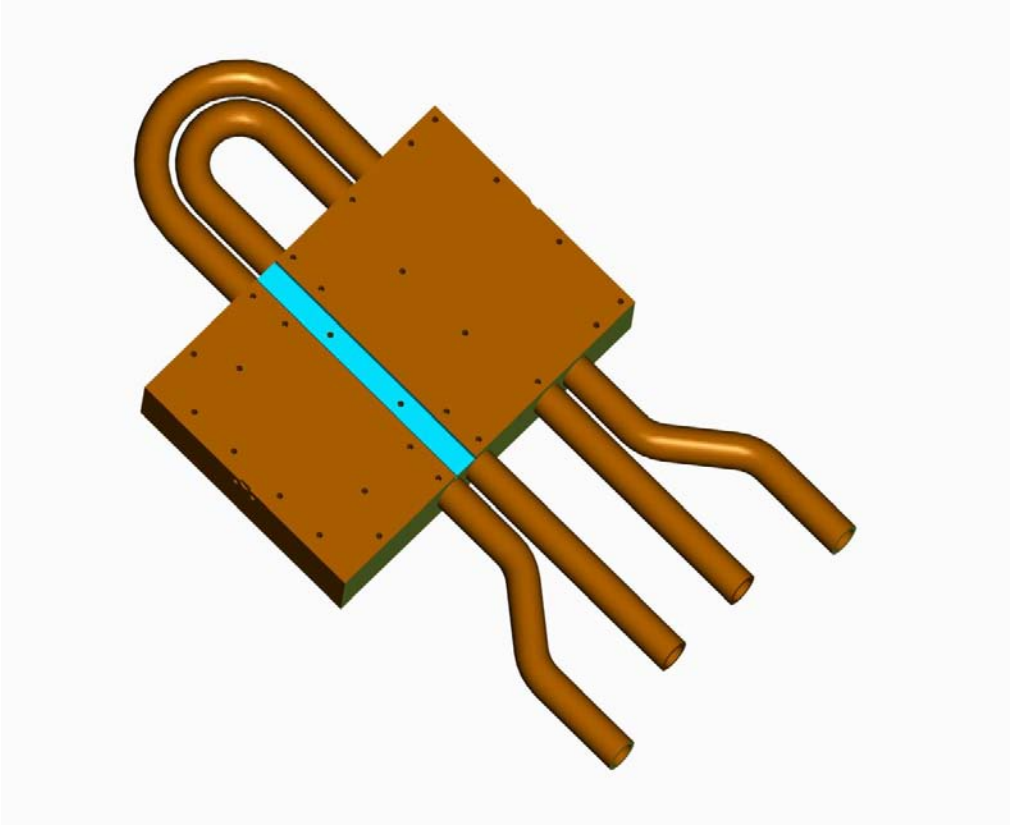
- We obtained two Freescale MRF6VP41KHR6 352.21MHz/1kW evaluation boards and assembled two amplifiers using “de-lidded” transistors supplied by Freescale

- 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*



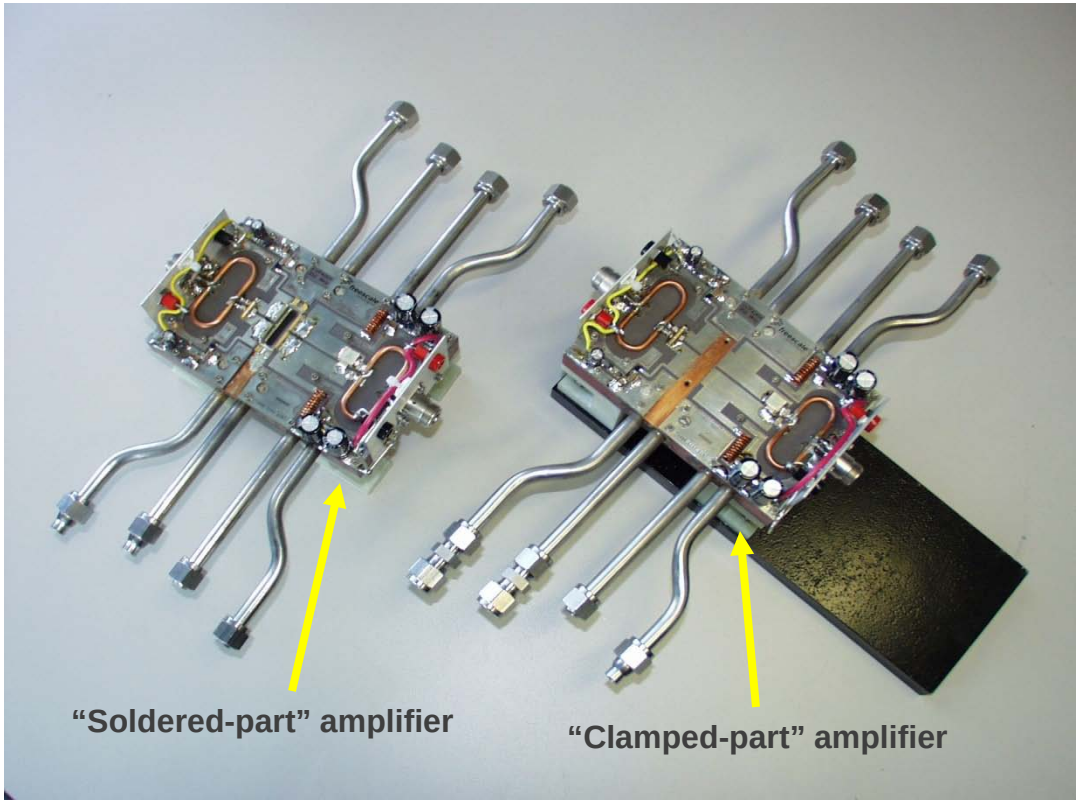
Modified APS cold-plate design

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*

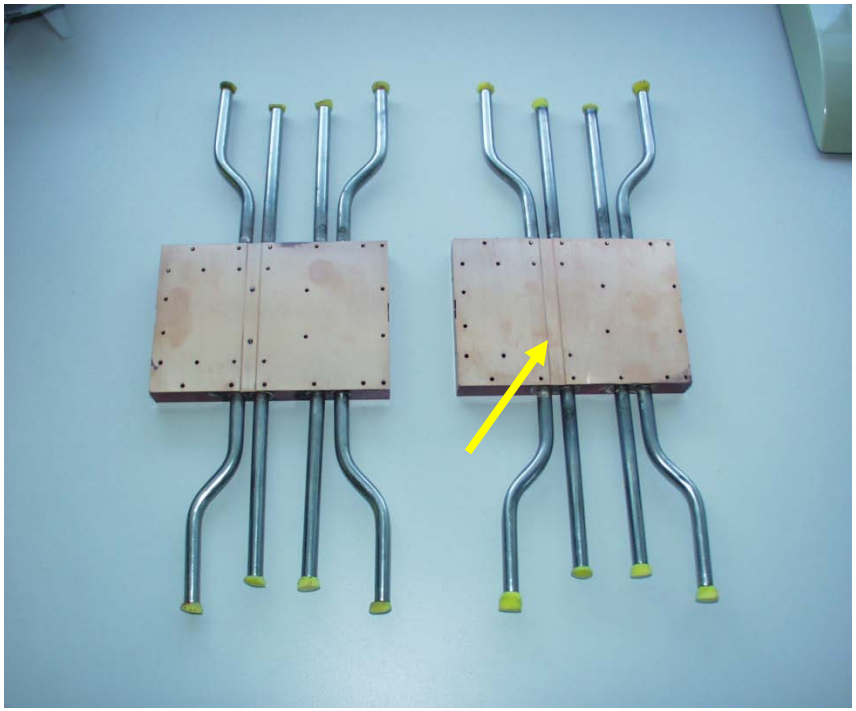
→ *Assembly was performed in stages using two solder alloys with different melting points*

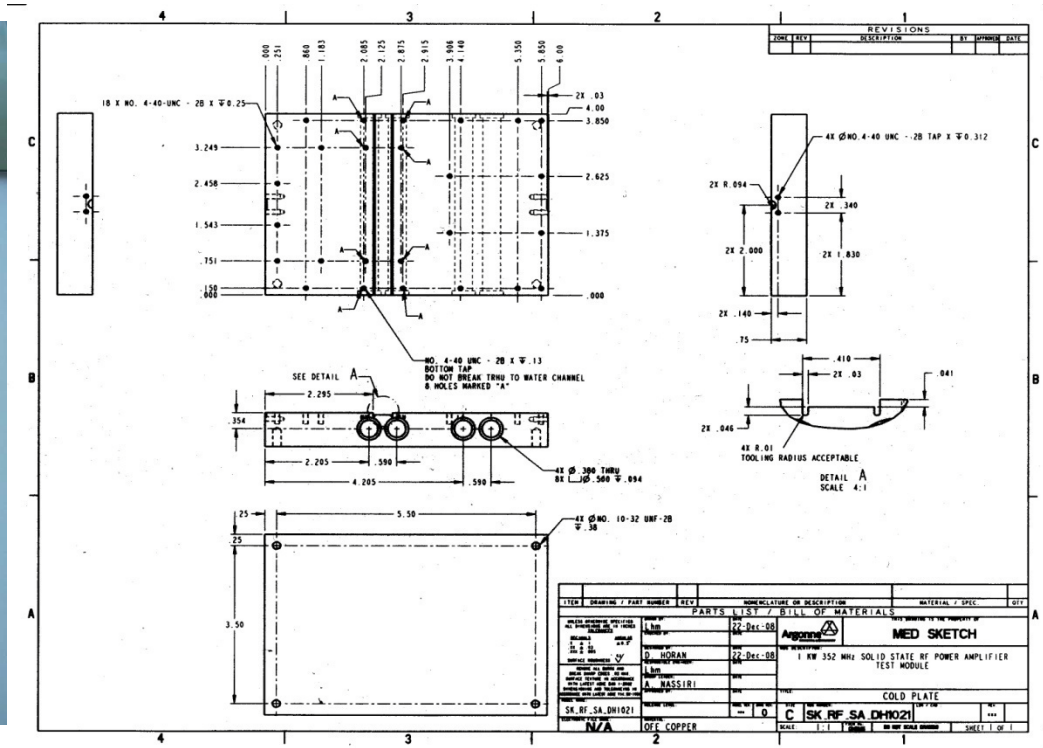


Completed amplifiers

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:



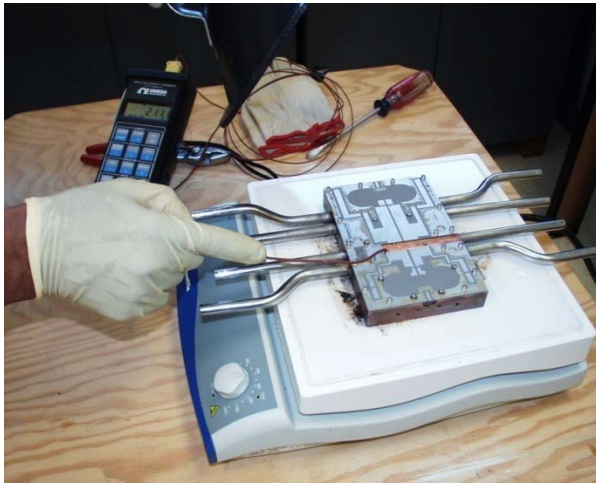


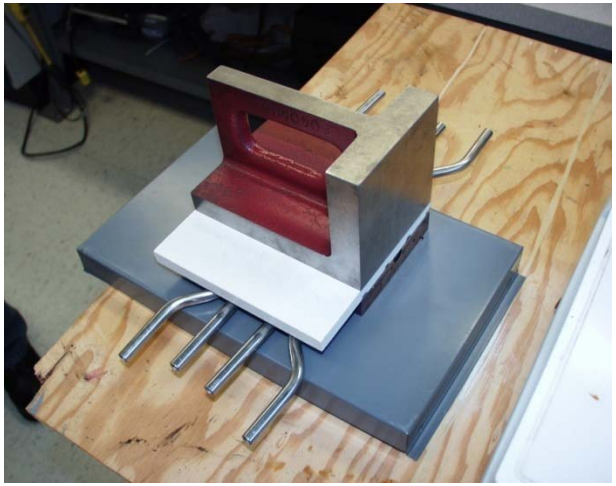
→ "Clamped-part" cold plate has 4-40 threaded holes to attach the transistor to the cold plate

→ "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°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***



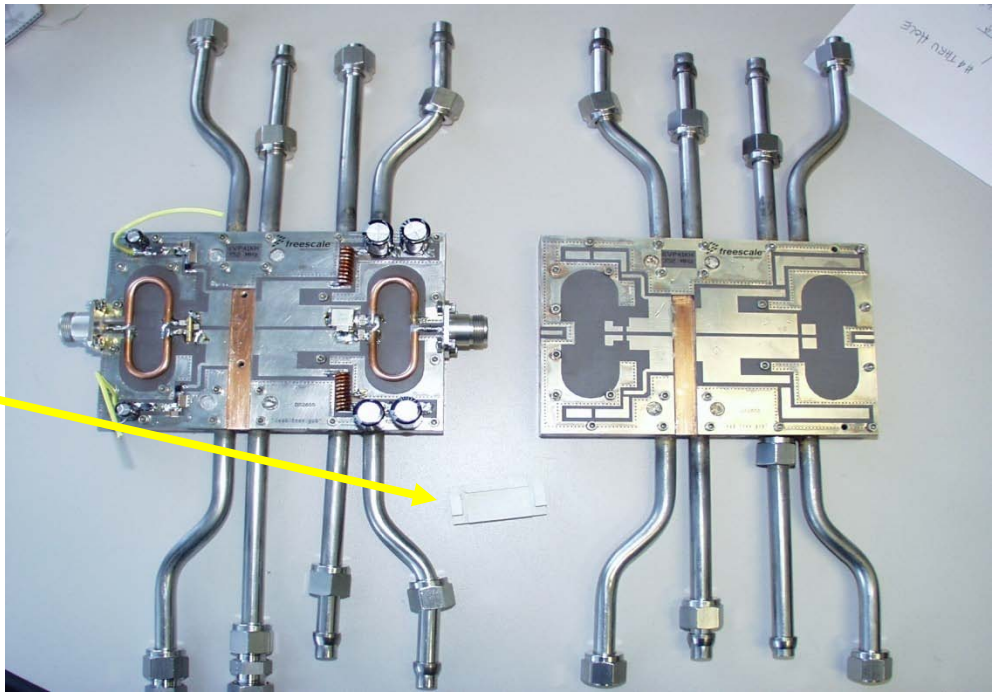


352-MHz 1kW CW Amplifier Construction

- 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***

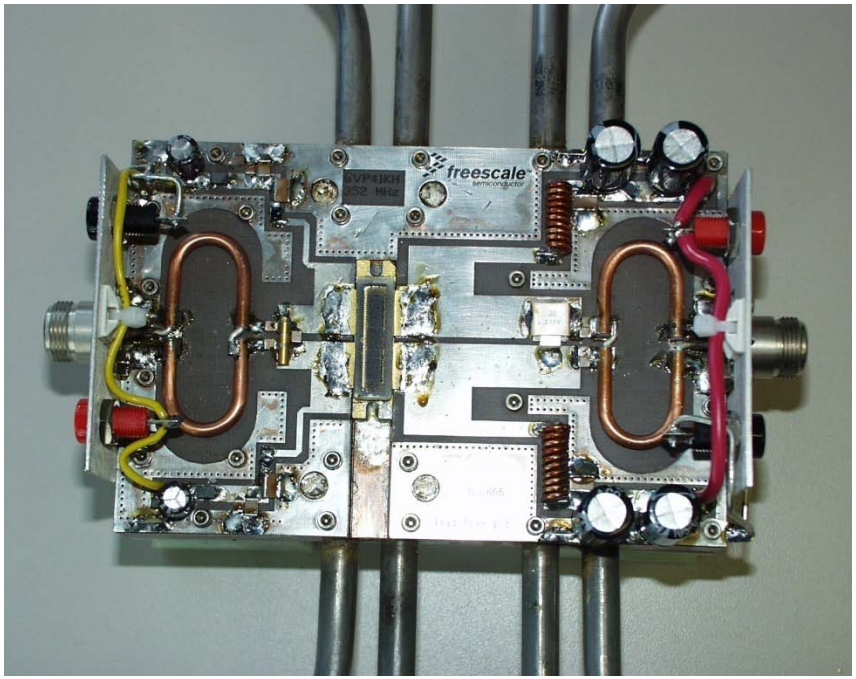


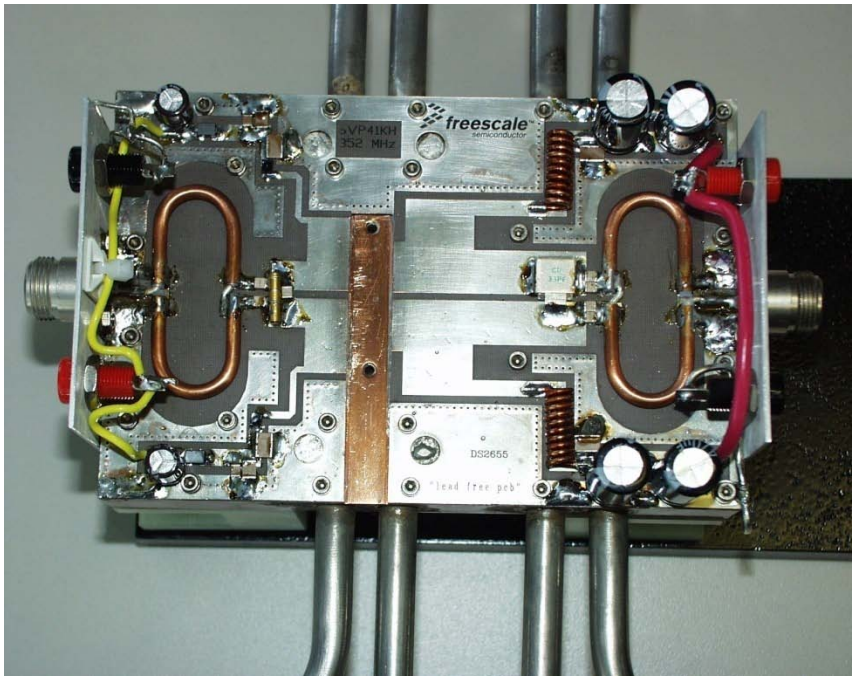
352-MHz 1kW CW Amplifier Construction

- 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

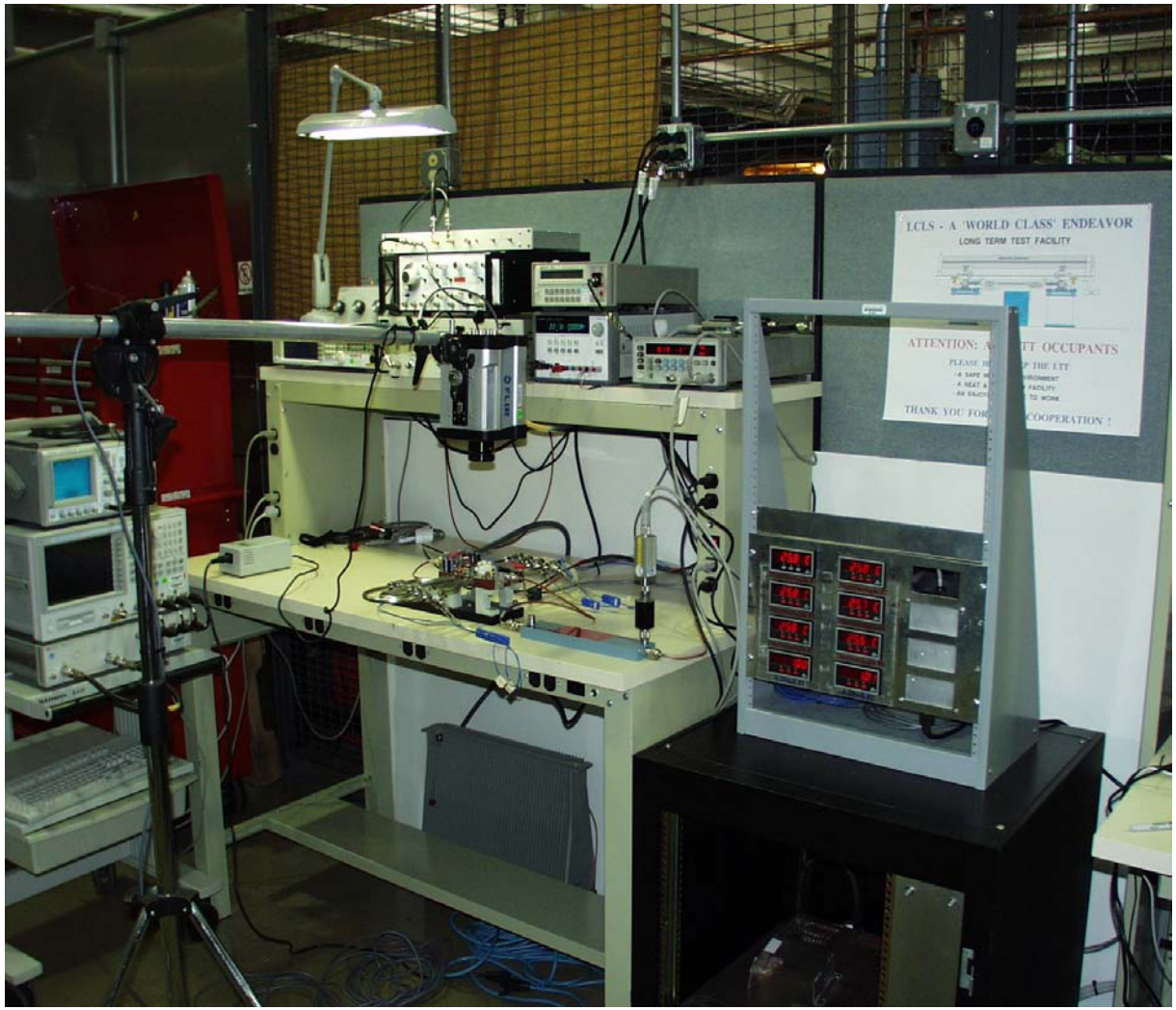
- The remaining assembly was completed by heating the entire assembly to 120ºC on the hot plate and using a 200-watt soldering iron to solder all connections that were thermally bonded to the cold plate.





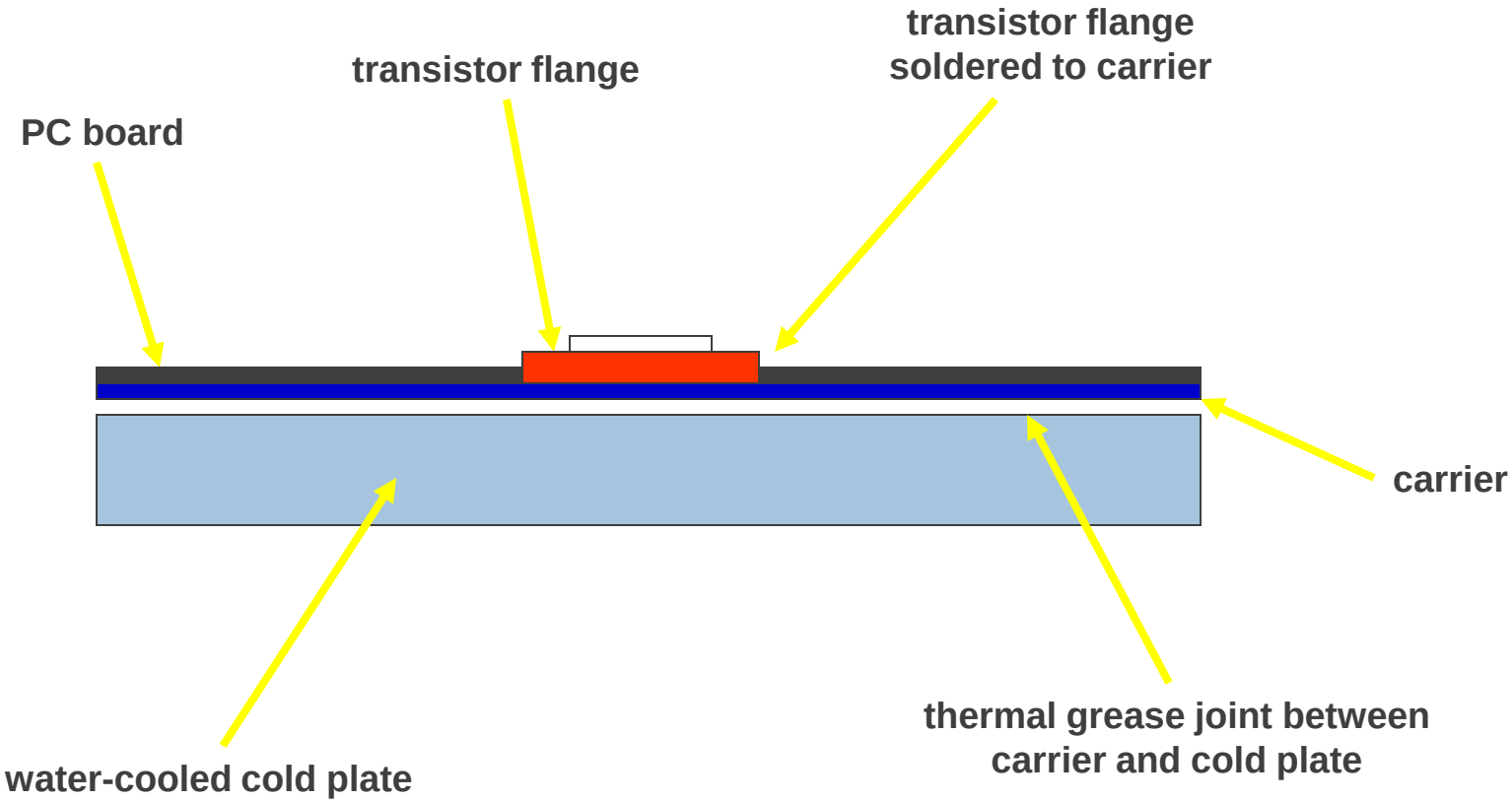
352-MHz 1kW CW Amplifier Test System and Plan

- 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



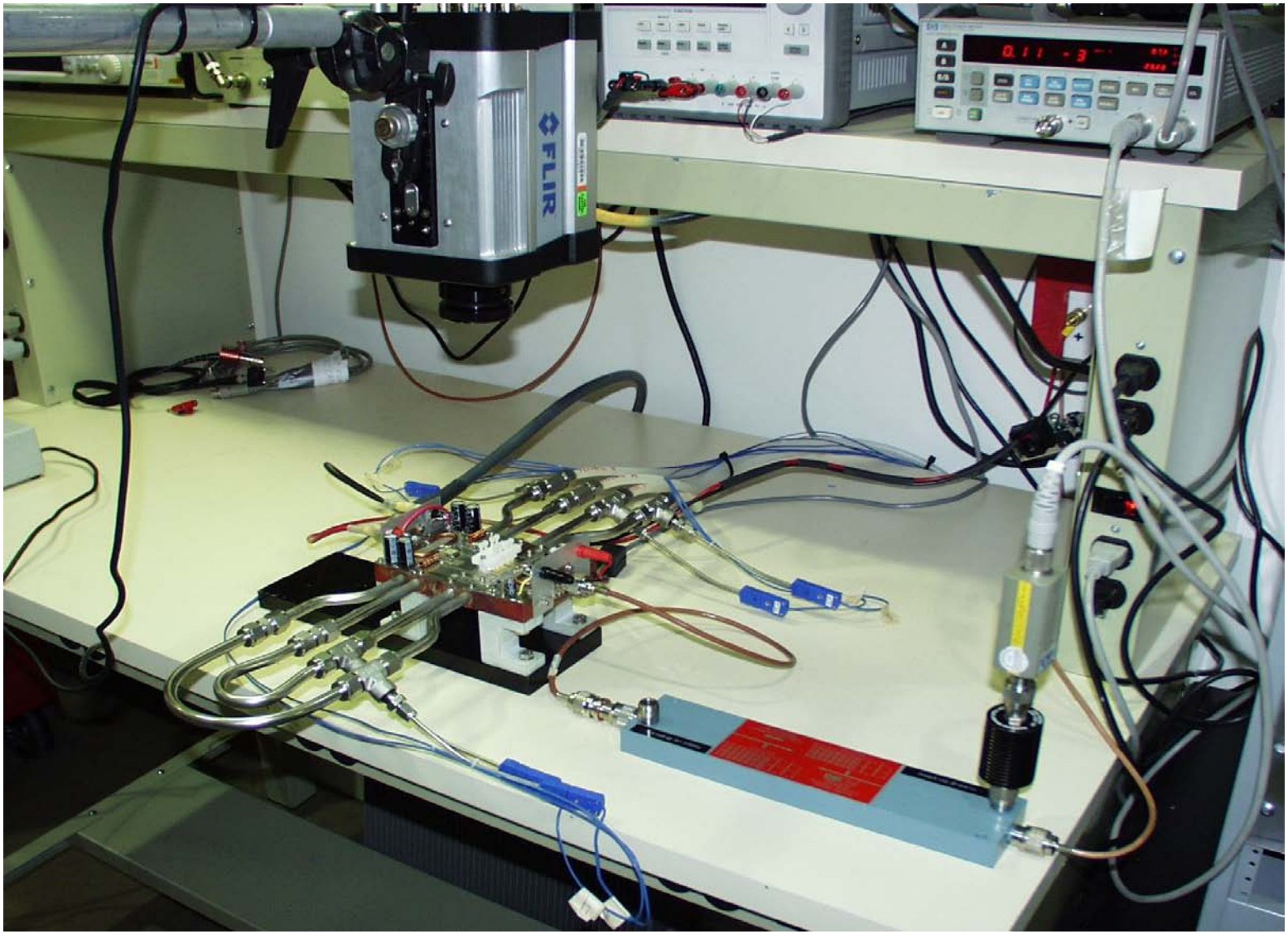
Lessons Learned from Test Results

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



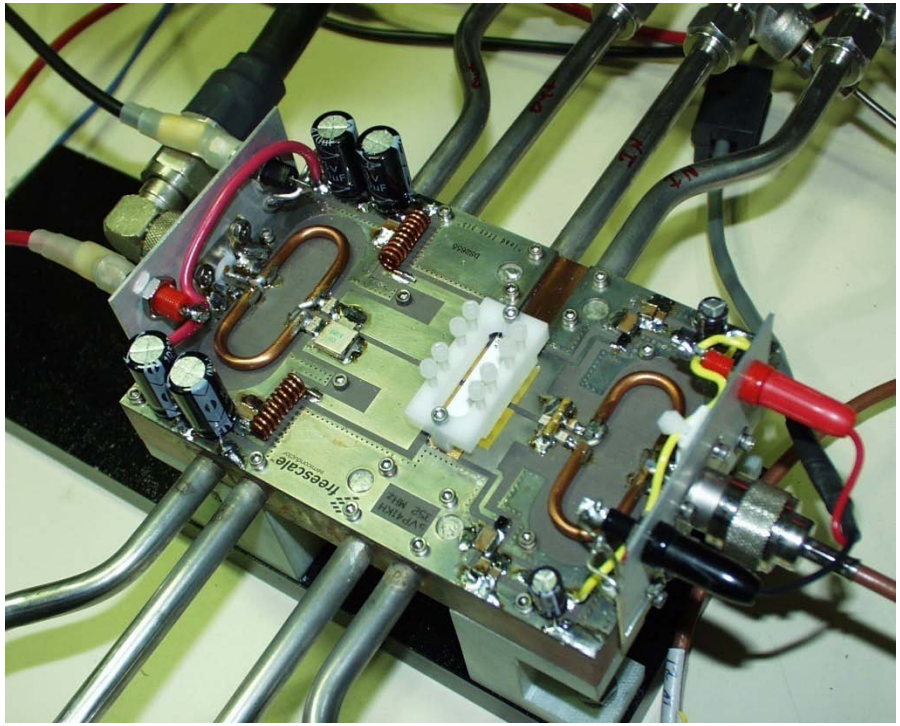
Carrier thickness of 4-6 mm will provide adequate thermal performance

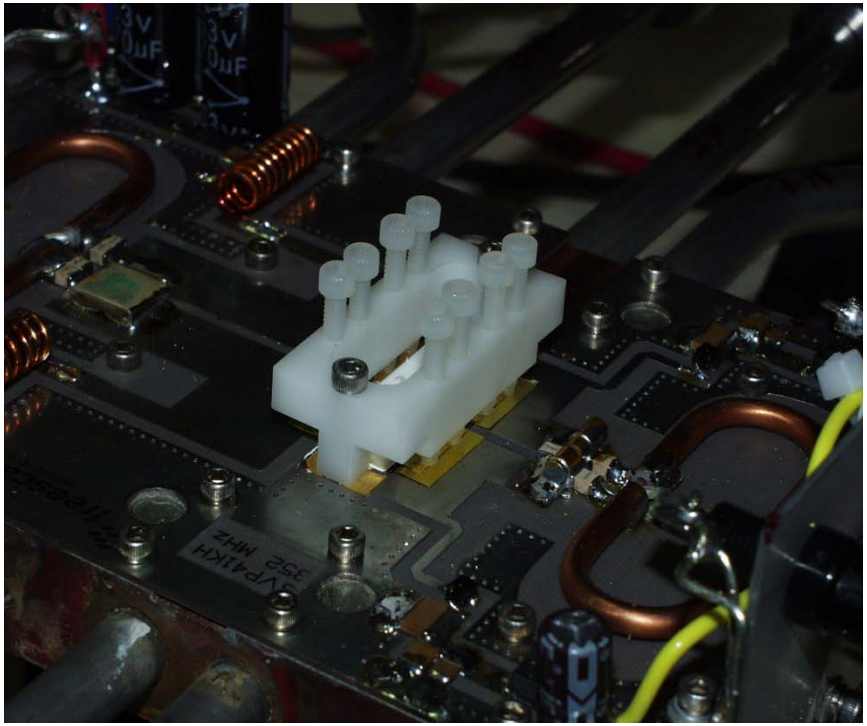
352-MHz 1kW CW Amplifier Test System and Plan



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%

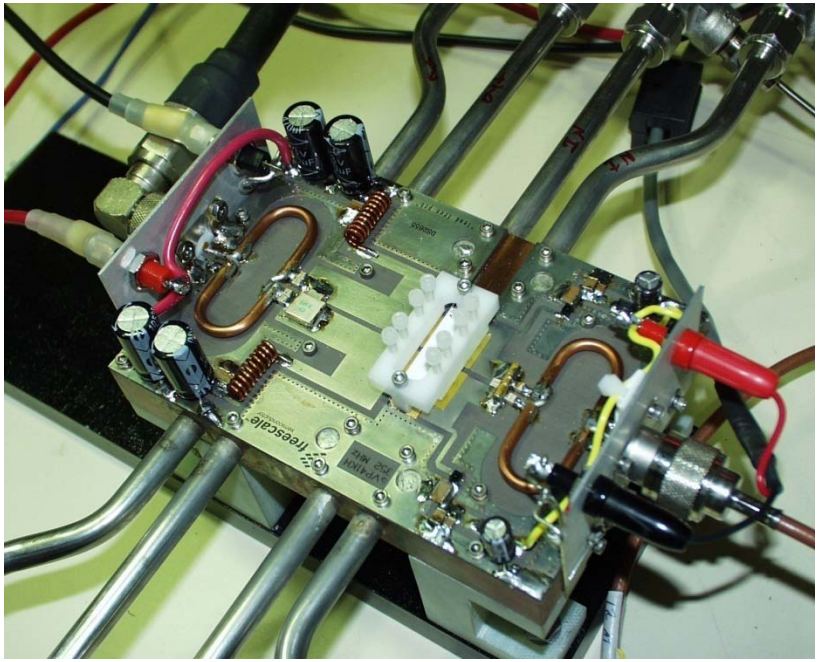
  → RF output ≈ 909 watts (derived from water calorimetric power calculations)

  → RF input = 8.53 watts

  →Input return loss = 10.3dB

  →RF gain ≈ 20.2dB

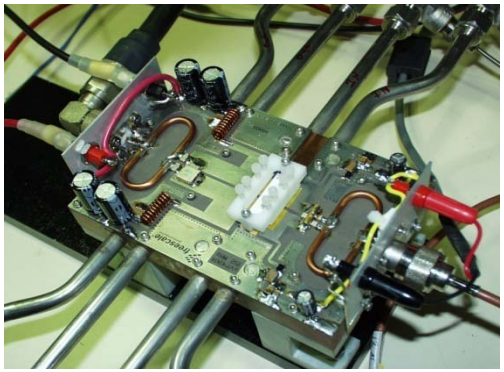
  →Water calorimetric power = 528 watts

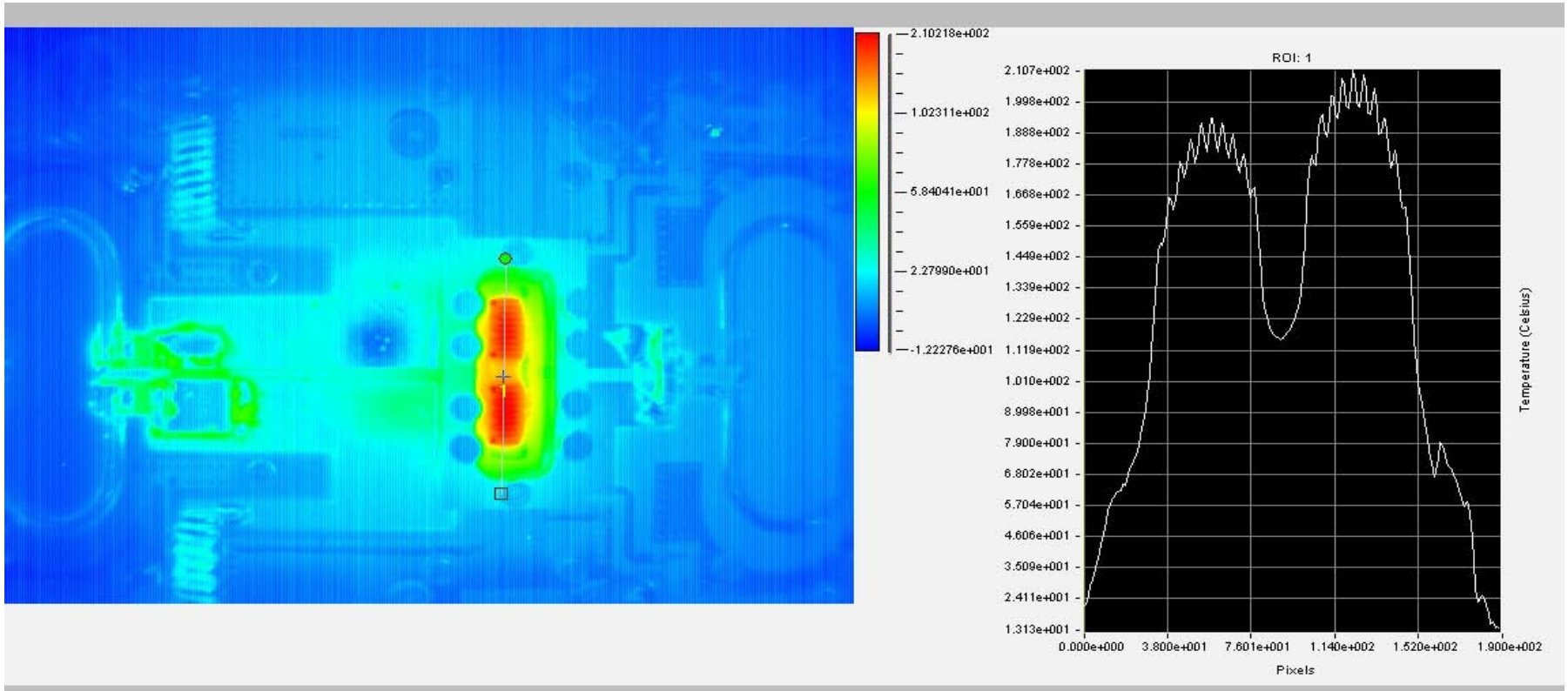


Initial efficiency was abnormally high (69.5%), so rf power meter readout at 1kW was suspect…….rf power was derived from power dissipation in water circuits

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%

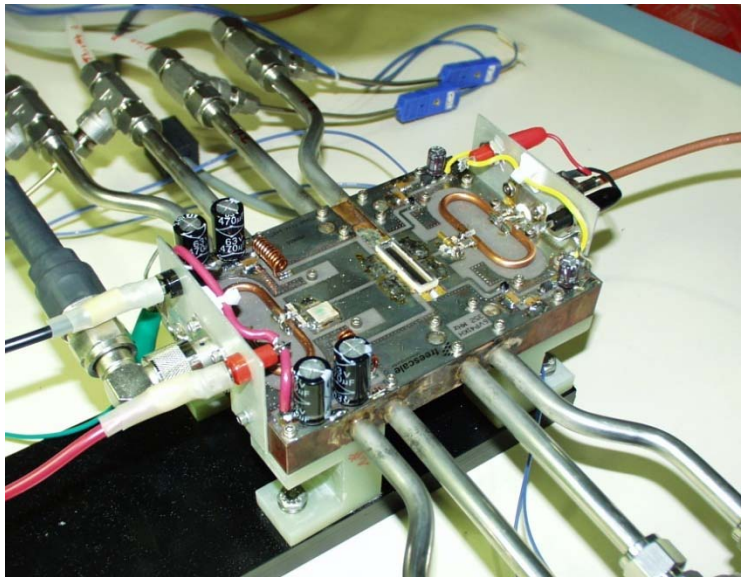
  → RF output = 1000 watts

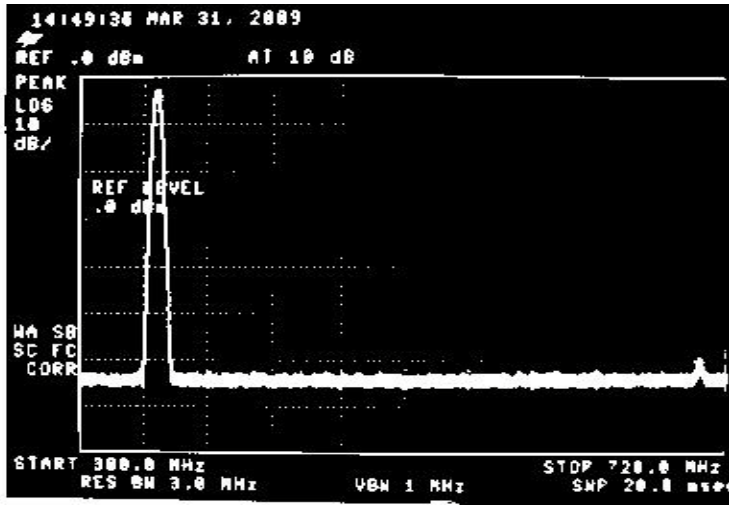
  → RF input = 8.32 watts

  → Input return loss = 10.07dB

  → RF gain = 20.79dB

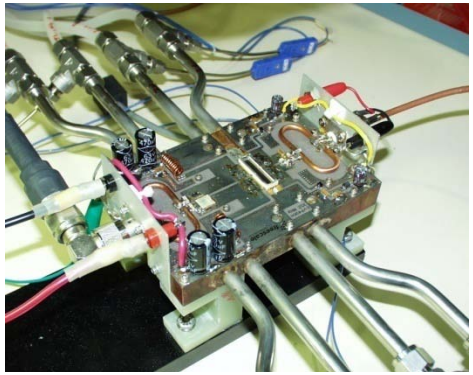
  → Water calorimetric power = 572.8 watts

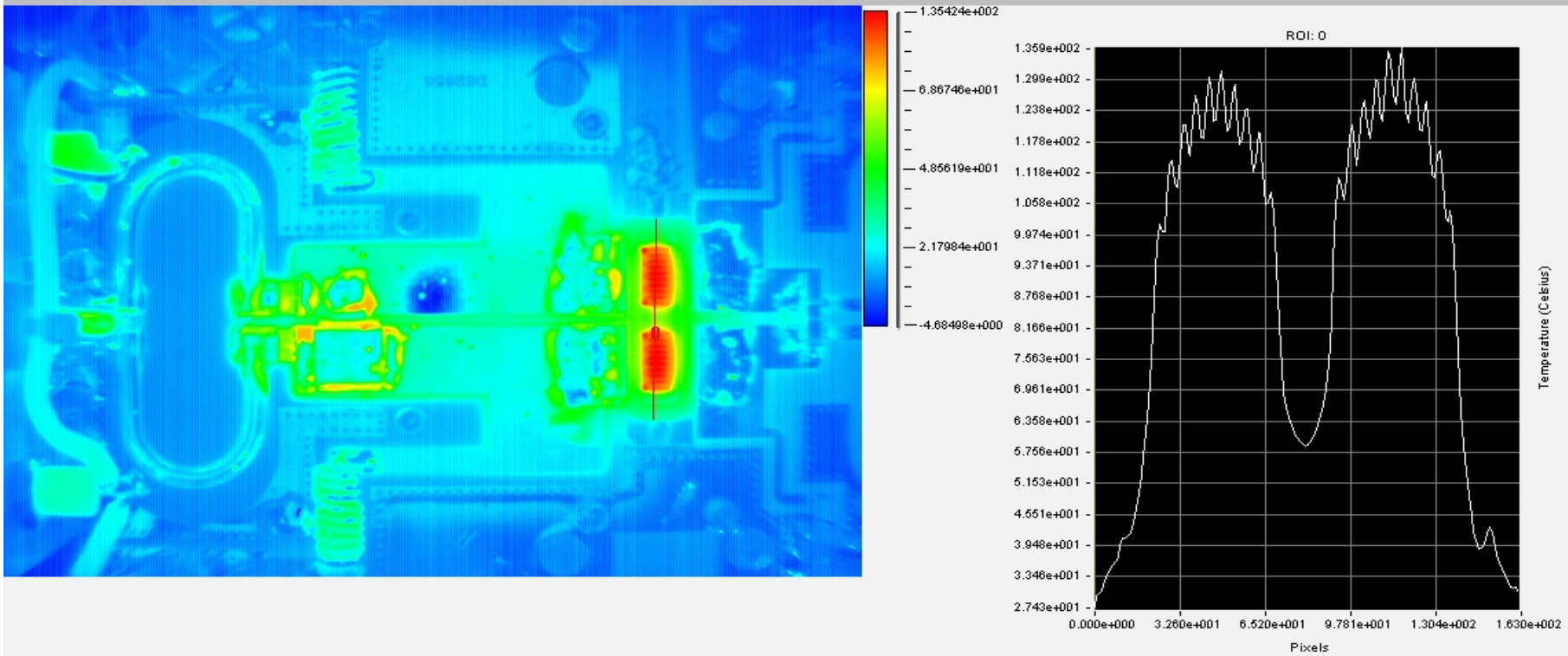




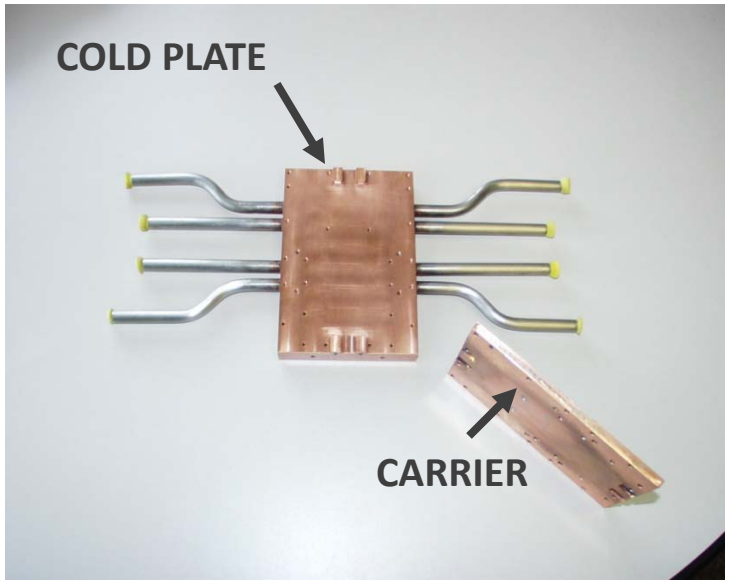
352-MHz 1kW CW "Soldered Part" Amplifier Test Results

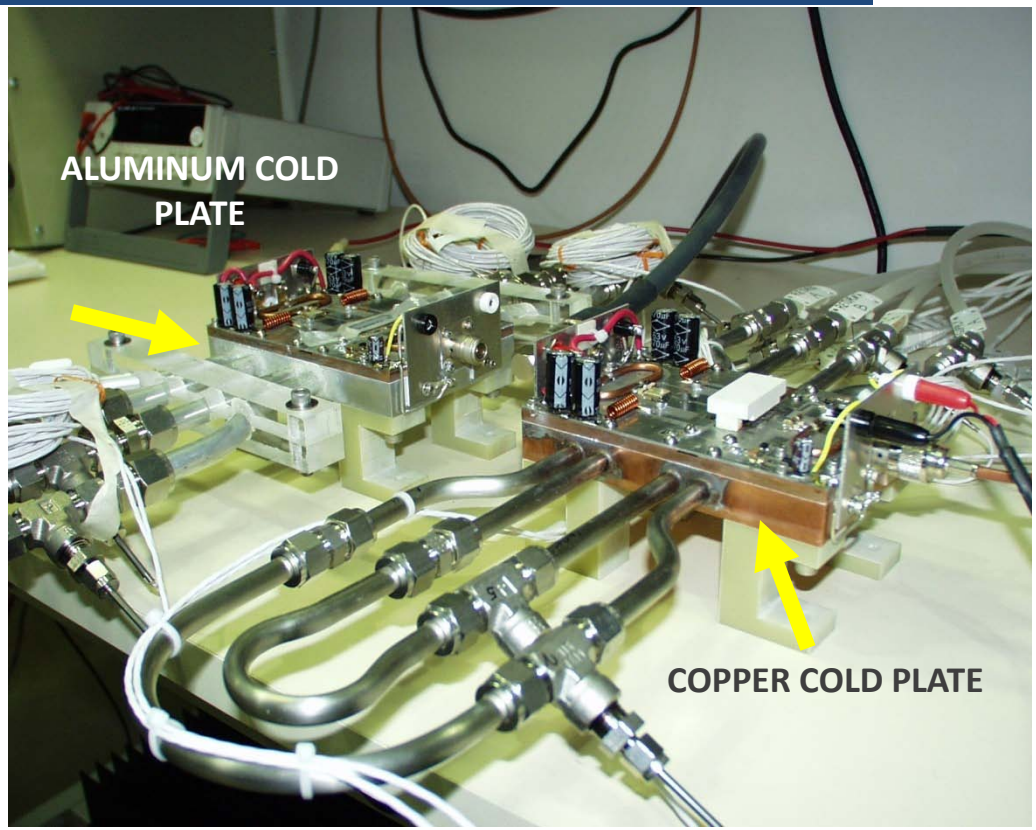
- **Maximum die temperature was 136ºC at 1kW output –** ***translates to a device MTTF of ~ 9E+6 hours.***
- **Temperature on top of flange between dies ~ 58ºC**
- ***As expected, the soldered-part construction technique offers more efficient cooling of device.***





Construction of "Carrier-Cold Plate" Amplifiers

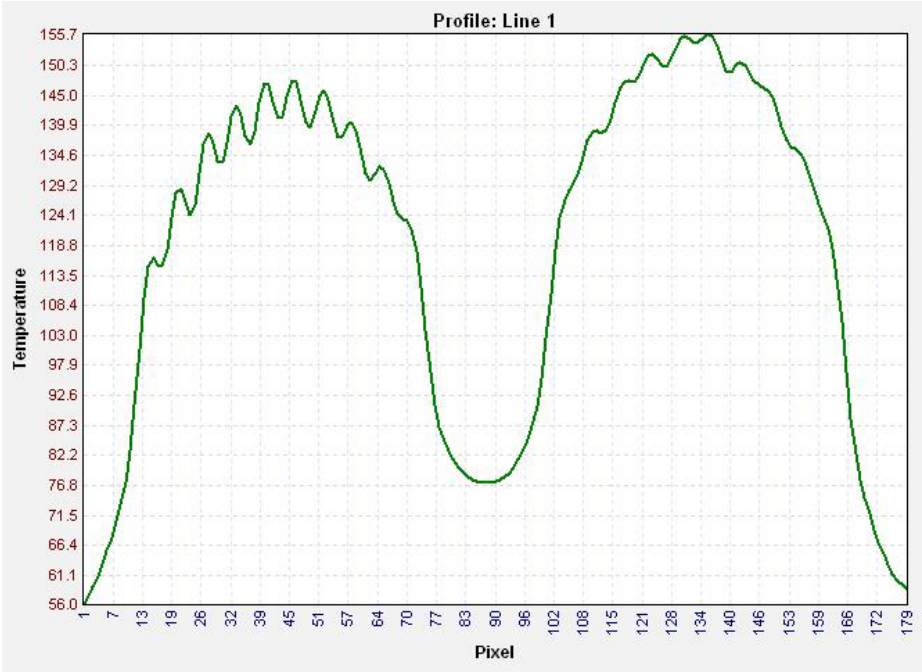


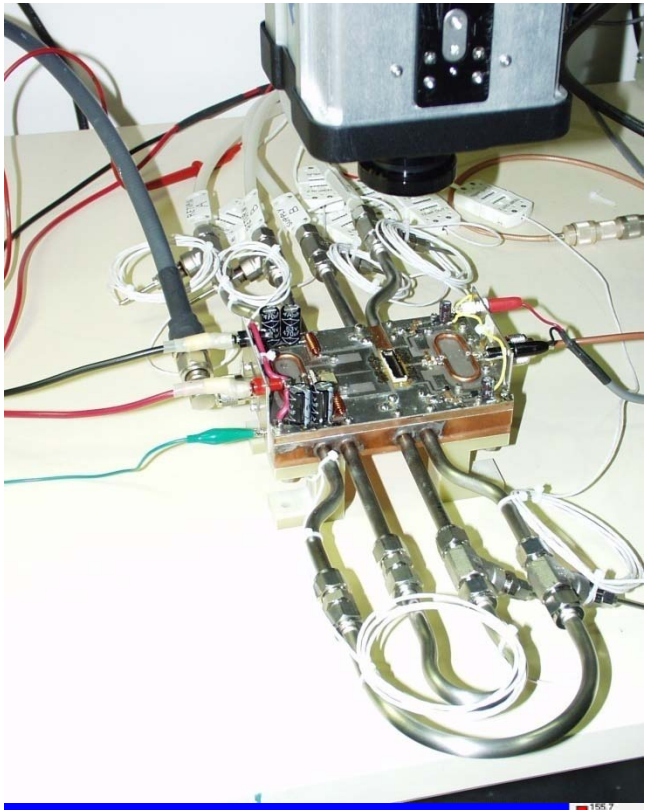


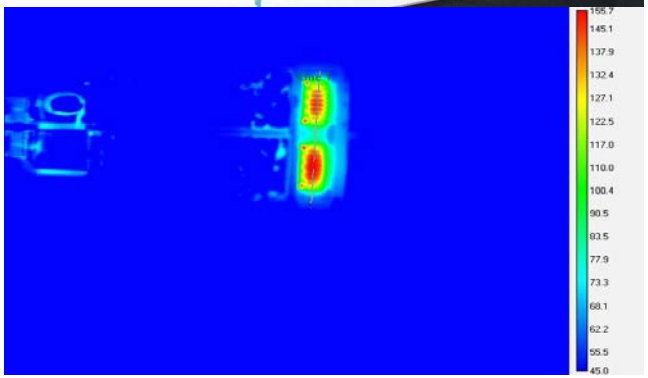
- Amplifier circuit board soldered to 0.25" carrier
- Carrier attached to cold plate by screws, using thermal grease for heat transfer
- Aluminum and copper cold plate built and tested

Testing of Copper Cold Plate Amplifier

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

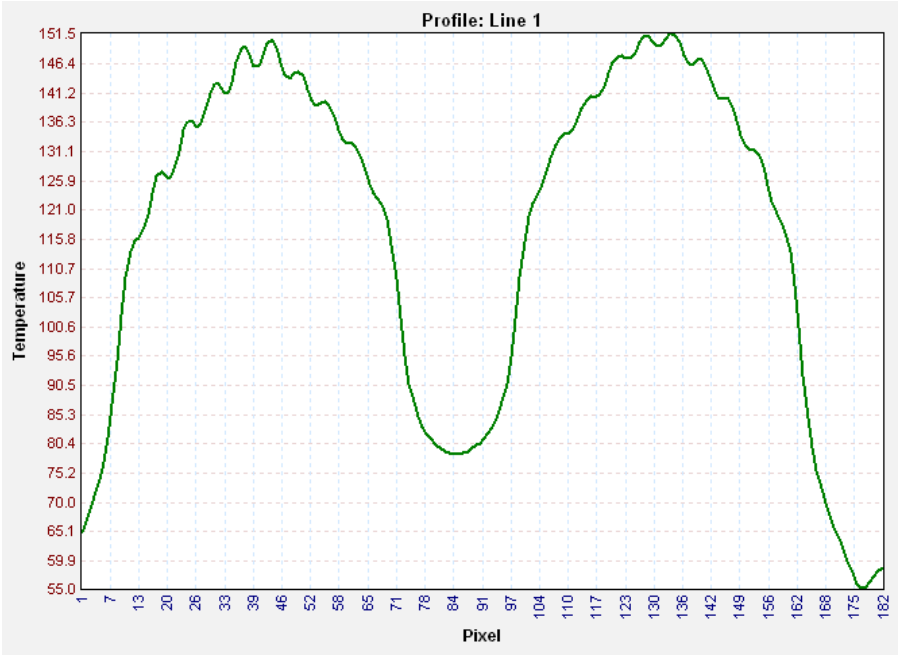


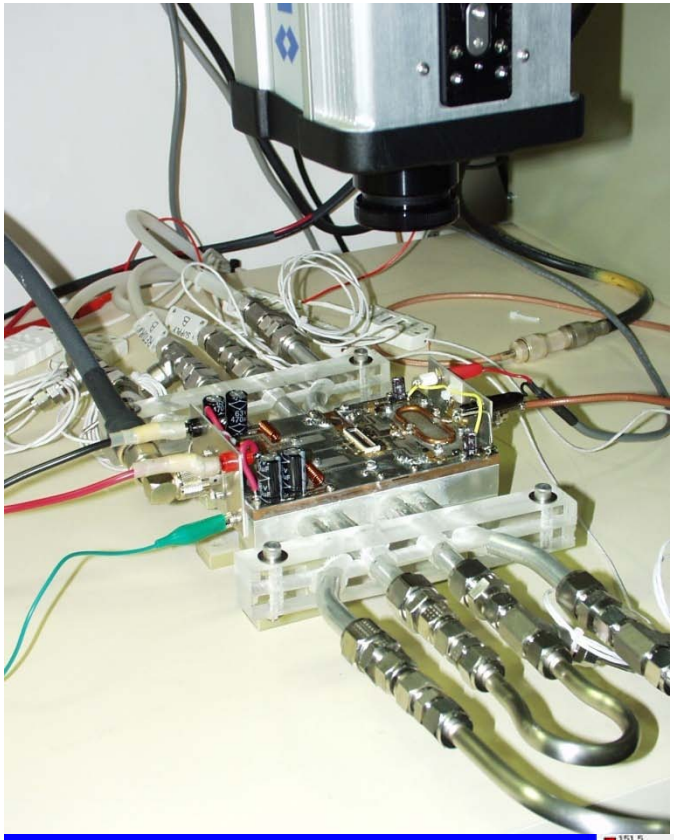


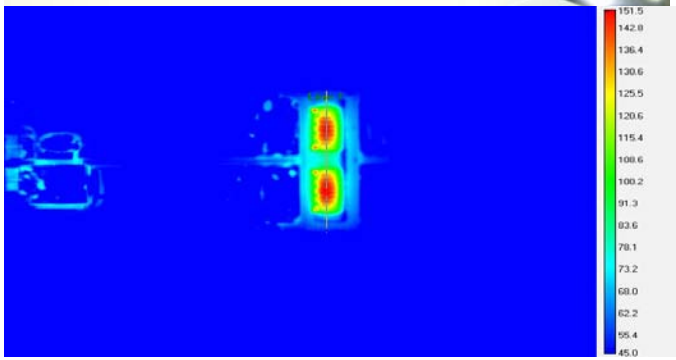


Testing of Aluminum Cold Plate Amplifier

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

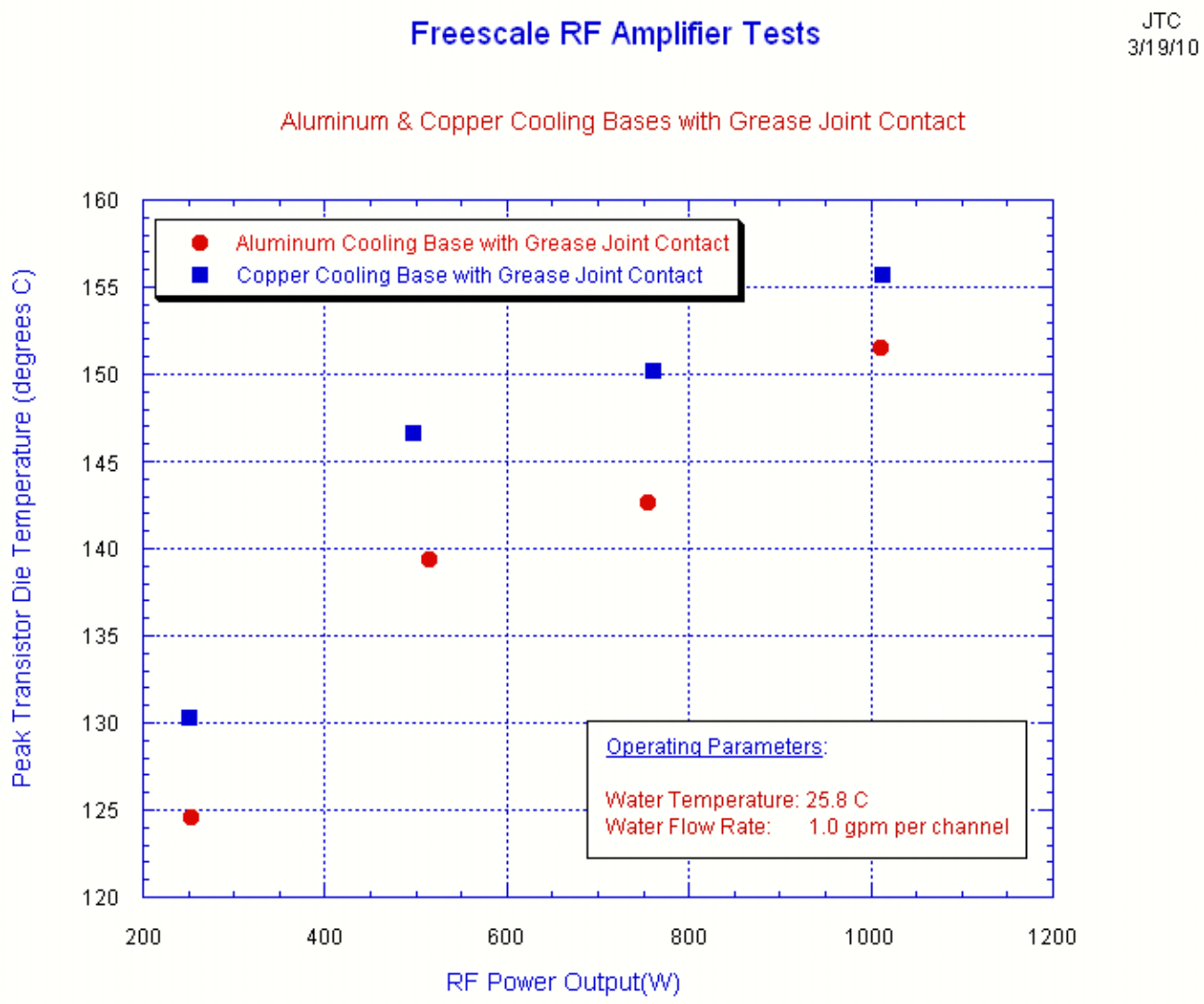






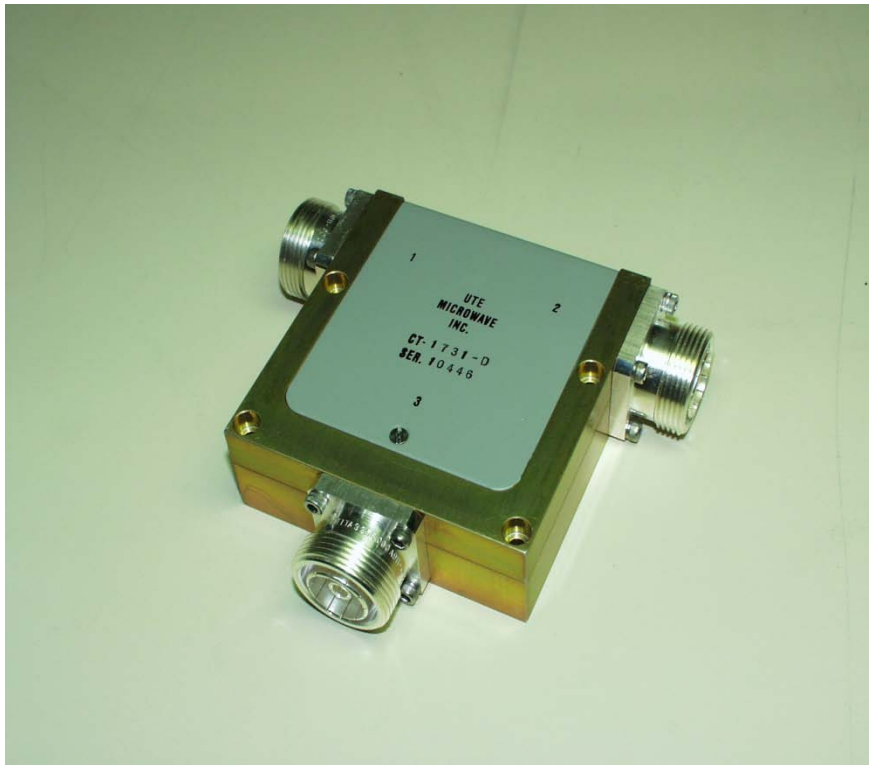
Thermal Performance of Aluminum and Copper Cold Plates

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



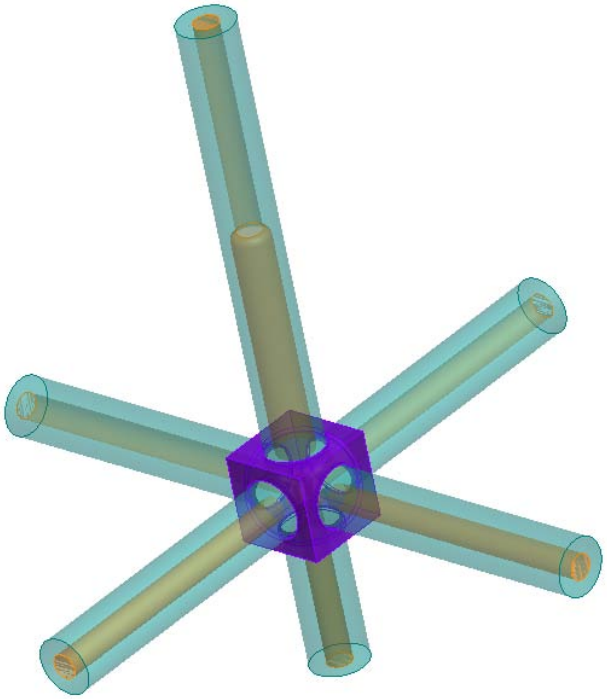
1kW Circulator Procurement and Test

- 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

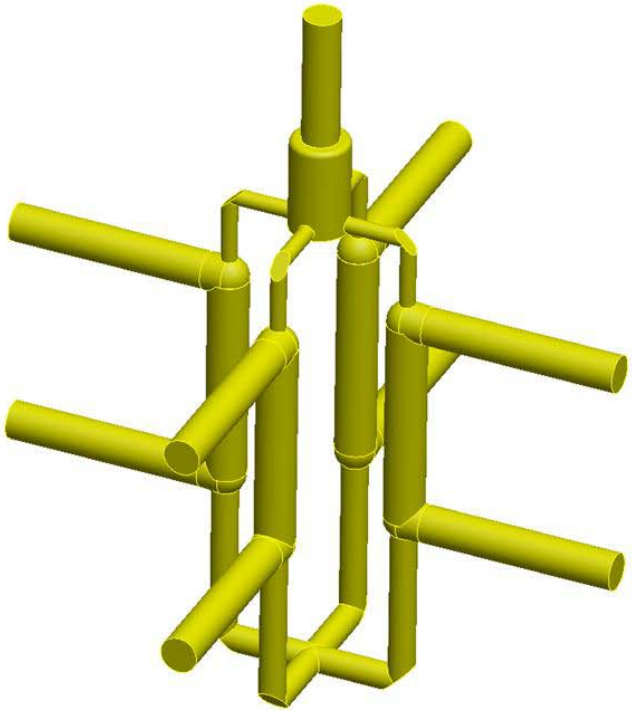


Design of Quarter-Wave 4-Way Combiner

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

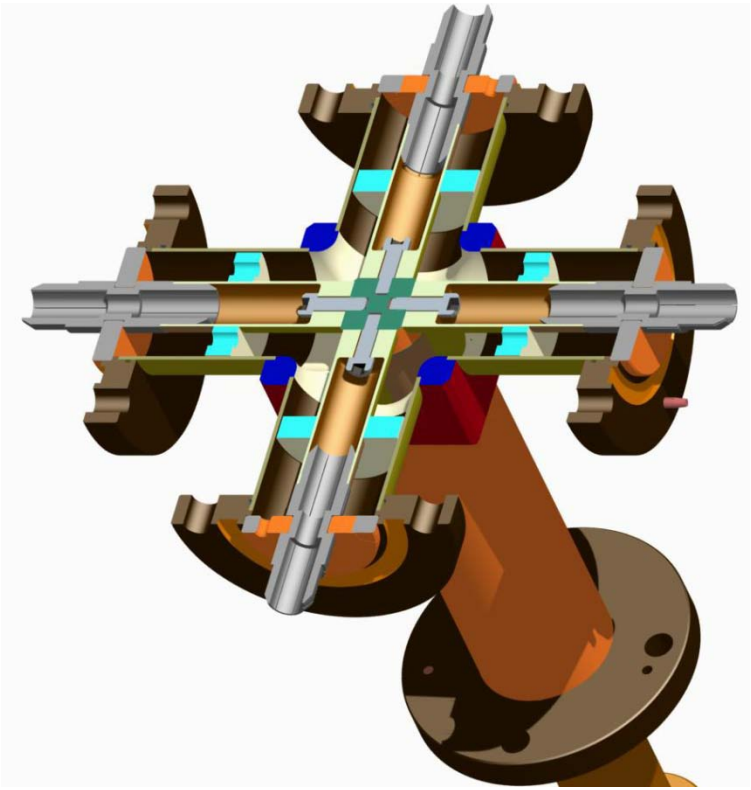


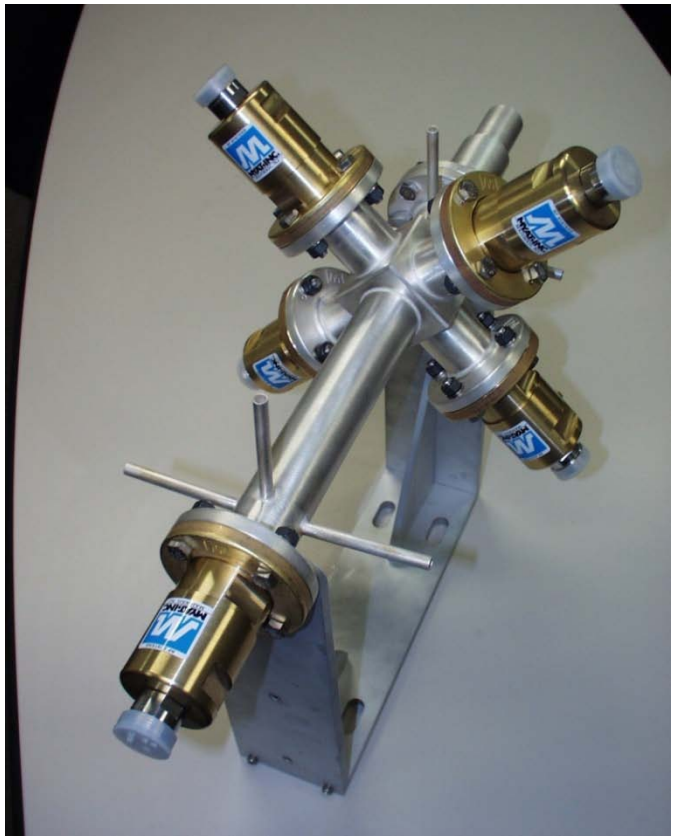
Standard quarter-wave coaxial combiner



Gysel Combiner

Design of Prototype Quarter-Wave 4-Way Combiner

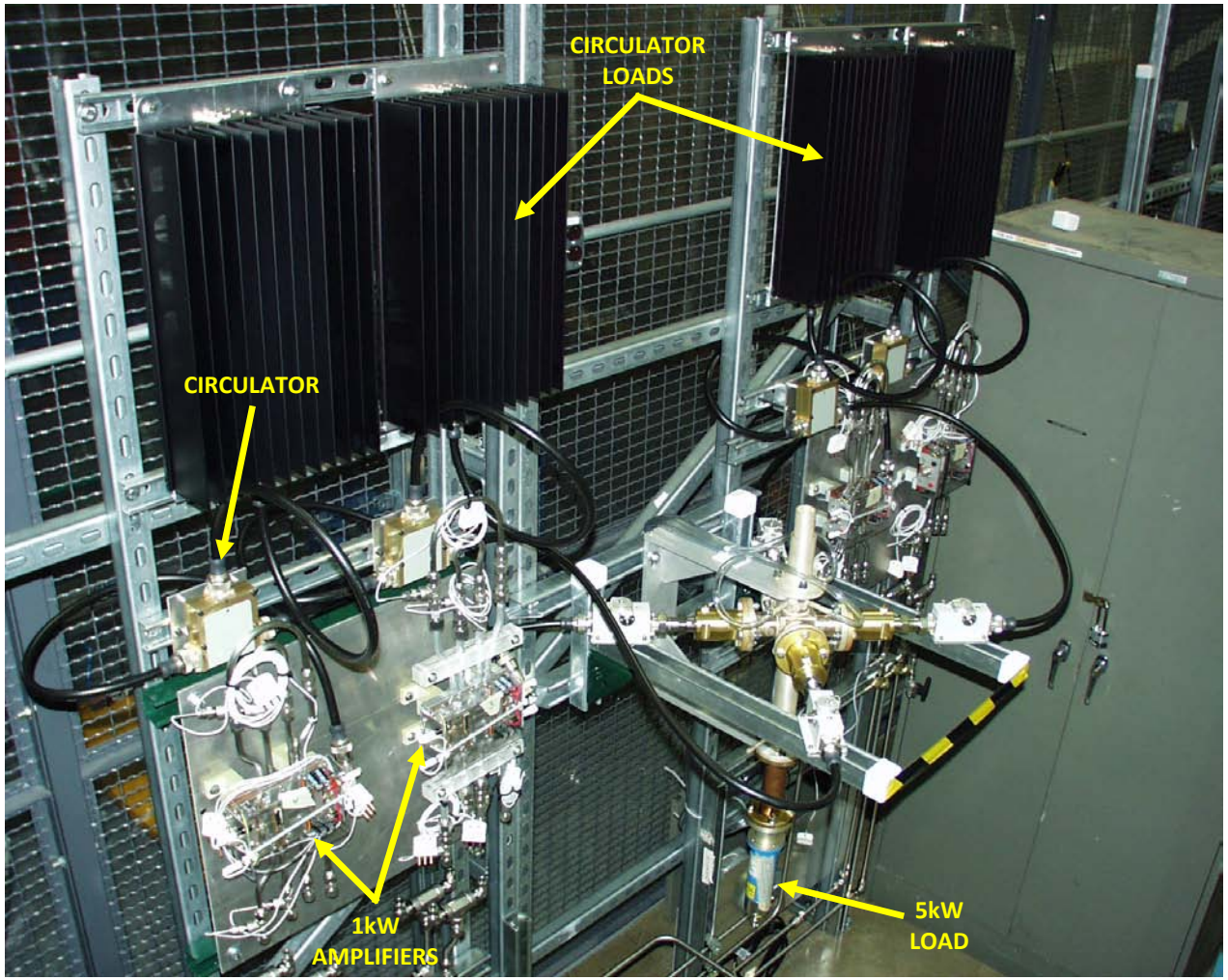




- Constructed with 1-5/8” EIA standard coaxial components
- Utilizes sliding shorting plunger for tuning
- 100-watt input test demonstrated expected performance

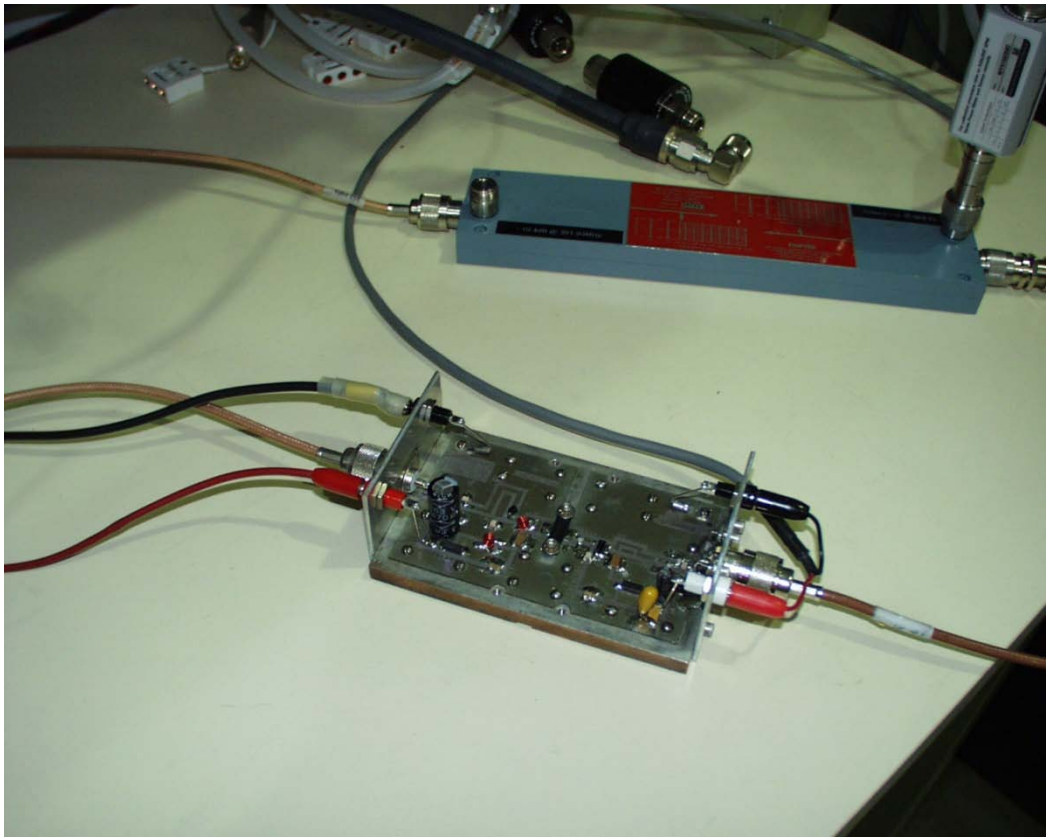
4kW Demonstration Amplifier System

- Construction in progress
- Drain voltage will be adjusted to maximize efficiency over 6dB rf output range
- AC line-to-rf output efficiency will be determined
- RF phase noise will be measured



352-MHz Driver Amplifier

- Uses Freescale MRF6V2010NBR1 LDMOS push-pull device
- Prototype circuit designed onto 220MHz evaluation board and modeled with ADS
- Measured performance in close agreement with model:



Measured Pout = 10 watts CW

→ ***Efficiency: 45.3% predicted***
42.8% measured

→ ***RF gain: 17.6dB predicted***
14dB measured

→ ***Input return loss: 3.58dB predicted***
3.49dB measured

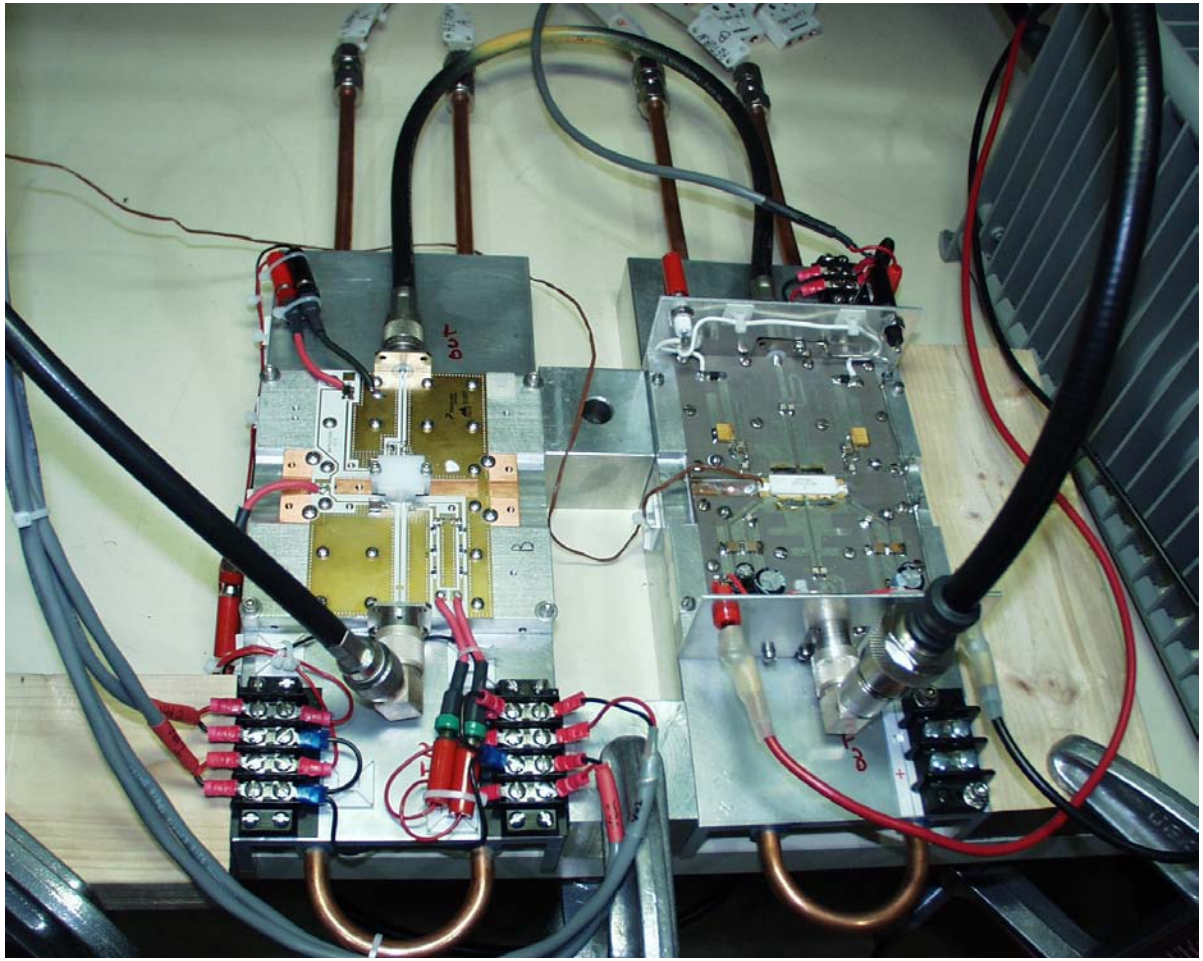
Solid-State CW RF Power at S-Band

- Freescale MRF6P27160H LDMOS push-pull device
- Tested at 2,815.00 MHz – *SPX operating frequency*

  → ***Pout = 144 watts CW***

  → ***55.8% efficiency***

  → ***13.9dB gain***



Conclusions From Initial Test Results

- The MRF6VP41KHR6 device is a possible candidate for the APS 352-MHz solid-state amplifier project.
- The existing APS 90ºF de-ionized water system could be used to cool the amplifiers.
- Carrier + Cold Plate construction has managable thermal impact
- Passive components and circuit board must be made more robust for continuous 352-MHz CW output at 1kW.
- High power CW solid-state amplifiers at S-band are possible

Plan for FY10 – FY11

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
   → Efficiency optimization using dynamic drain voltage adjustment
   → Performance of combiner compared to EM model

3. Continue rf circuit design for APS 352-MHz pre-driver, driver, and 1kW amplifier boards.

4. Build and test 4-way Gysel combiner

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