Upgrade Scenarios for the Advanced Photon Source RF Power Sources

Doug Horan
APS RF Group
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Outline

- **APS RF System Topology**
- **RF System Performance**
- **Concepts for RF Power Upgrades at the APS**
- **Solid State RF Power Development at the APS**
- **Recent Hardware Failures**

APS 350-MHz RF Power Sources

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

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

→ ***Each klystron requires a dc input power of ~ 88kV/14A dc to support 102mA operation***

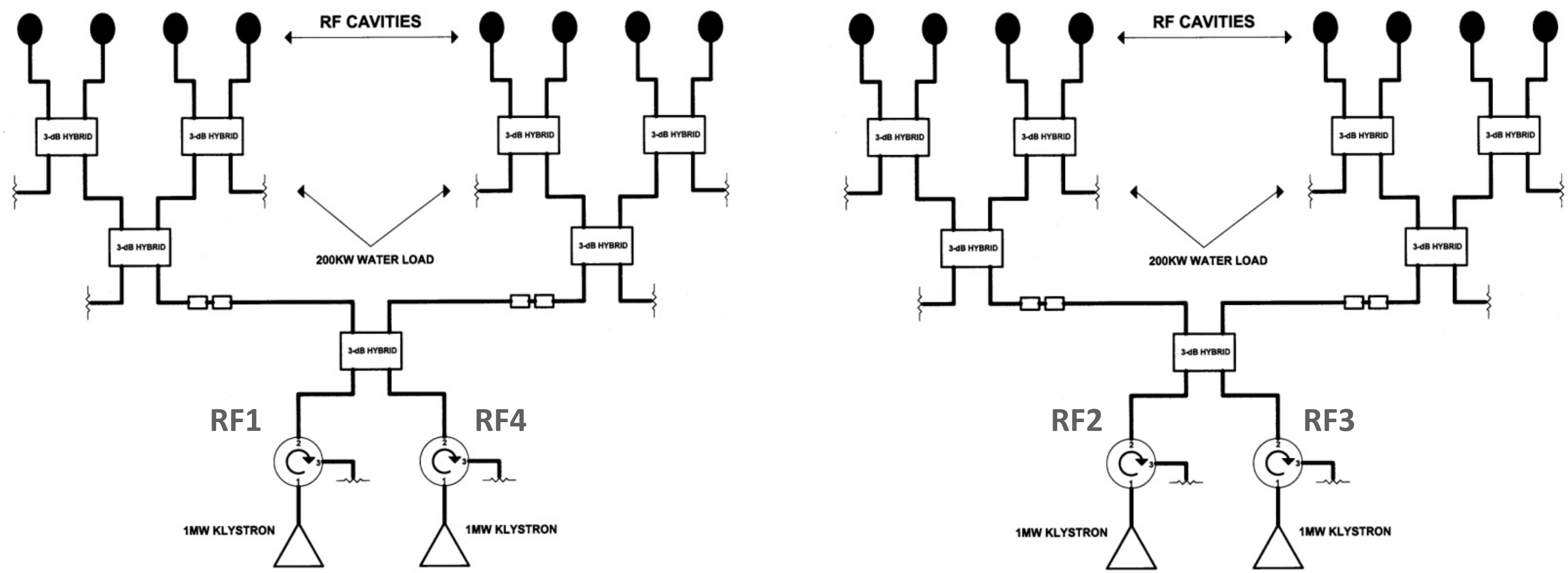
→ ***Klystrons are cooled by 450 GPM of DI water at 90ºF supply temperature***

→ ***Typical rf output power for storage ring rf stations is ≈ 675kW cw***

352-MHz/1.1MW cw klystron inside radiation shield enclosure

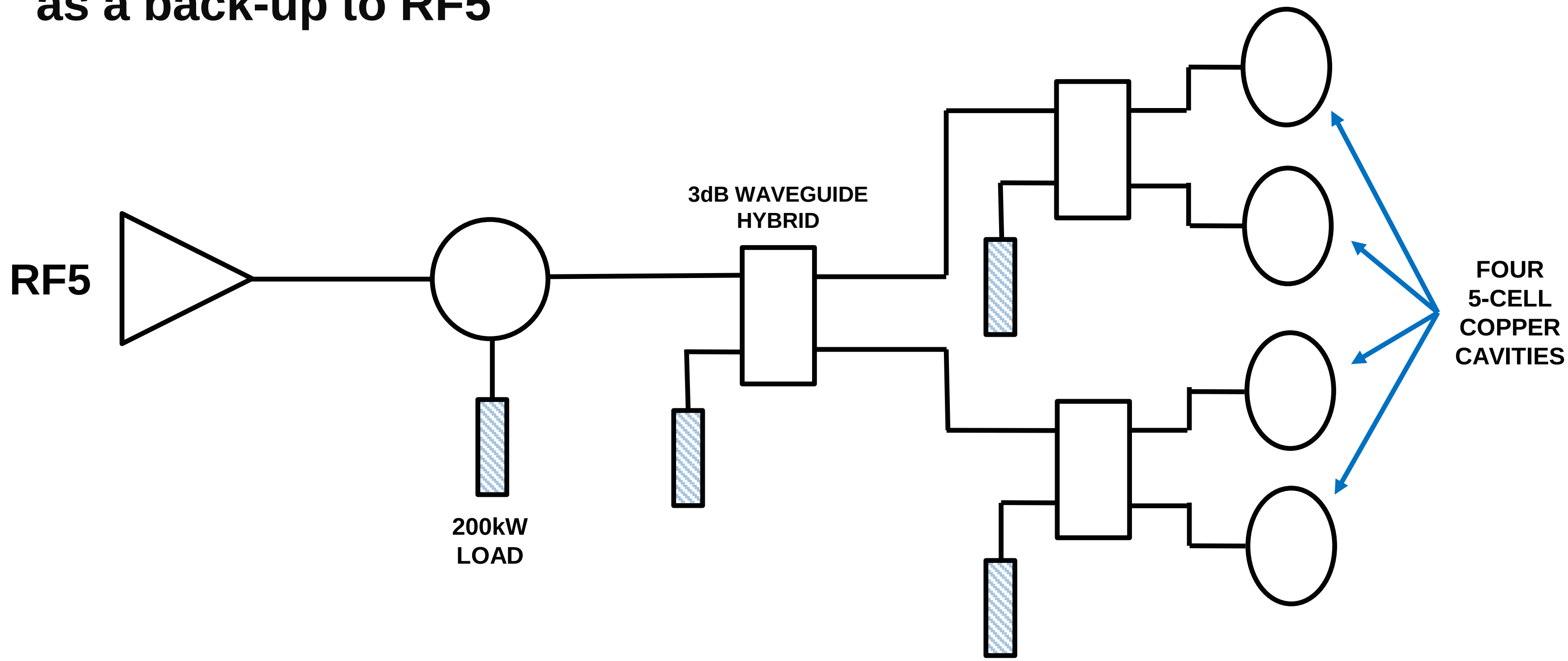
APS Storage Ring RF Topology

- Waveguide switching system provides twelve modes of operation with different combinations of rf systems
- Routine storage ring operation is 103mA maximum stored current in "top-up" mode – *APS Upgrade operation will be 150mA*
- Requires two klystrons driving storage ring, each operating at ~ *675kW CW for 103mA*, and ~ *800kW for 150mA*
- "Offline" rf stations are in diode mode at 70kV/5A



APS Booster RF Topology

- **Uses one 352-MHz/1-MW klystron (RF5) operating at 68kV/11.5A**
- **RF drive is 253ms ramp from 5kW to 400kW peak at 2Hz repetition rate → *400kW peak, ~ 120kW average power***
- **Waveguide switching system allows storage ring station RF3 as a back-up to RF5**



APS RF Upgrade Concept

- **Develop a reliable and rugged 352-MHz/200kW cw rf source using one of the following rf amplifier technologies:**

  → Conventional klystrons

  → 200kW multi-beam IOT -- *presently under development*

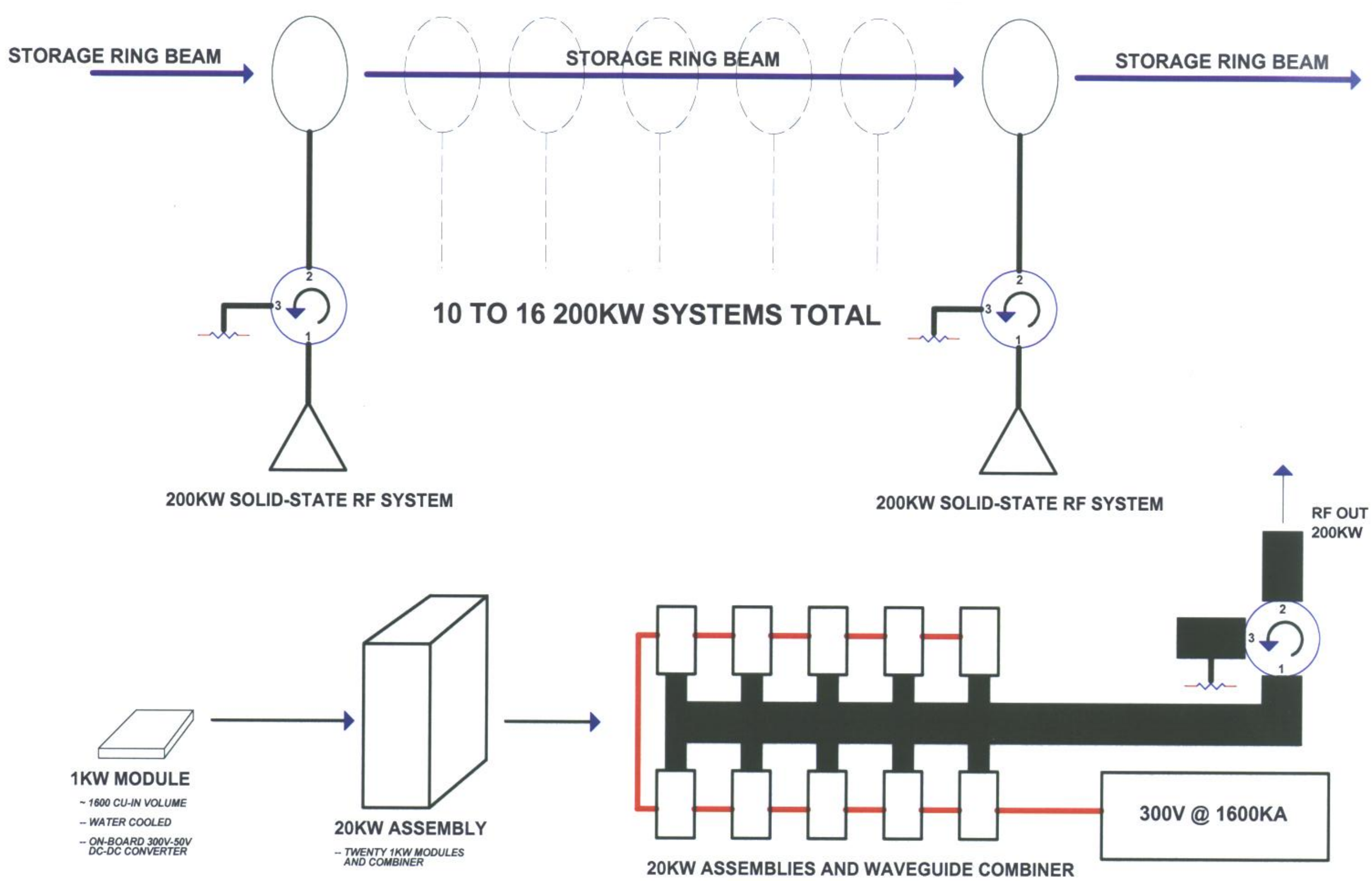
  → Solid state -- *under investigation*

- **Reconfigure storage ring rf system topology to one 352-MHz 200kW source per cavity, 10-12 cavities total**

- **Purchase prototype 200kW rf system and evaluate performance on the APS 352-MHz RF Test Stand**

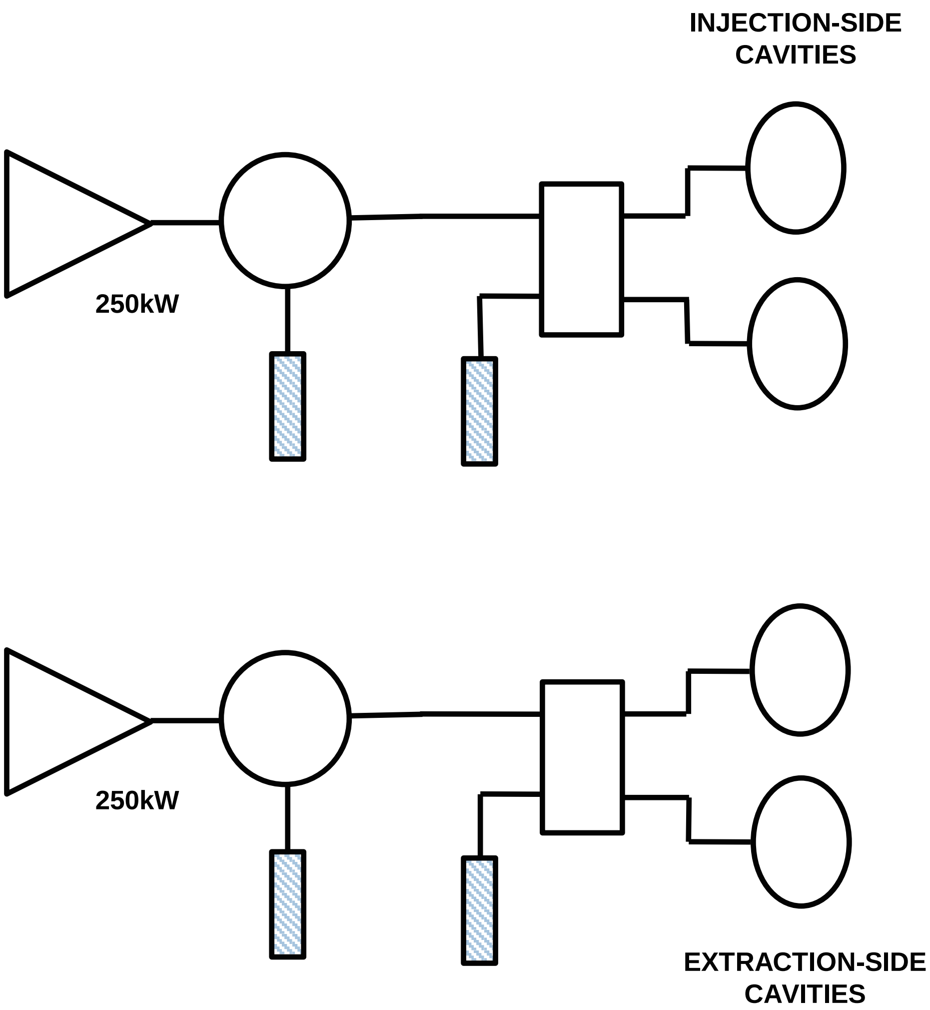
- **Replace Booster rf system with two 250kW solid state amplifiers, each driving two rf cavities**

APS Solid State Upgrade Concept



Solid-State Booster at APS?

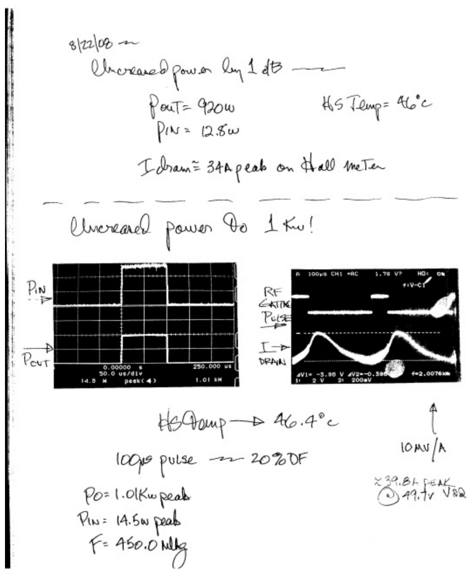
- Seems most possible cost-wise:
  ≈ *$4-6M??*
  → *Would not affect SR rf systems*
- Less disruption to APS operation during installation
- Assuming 60% overall efficiency, would reduce ac line load by
  ≈ 600kW
- May fit in available space due to 90^0 orientation of APS booster rf
- Two 250kW systems would provide 100kW of headroom over present booster operating point

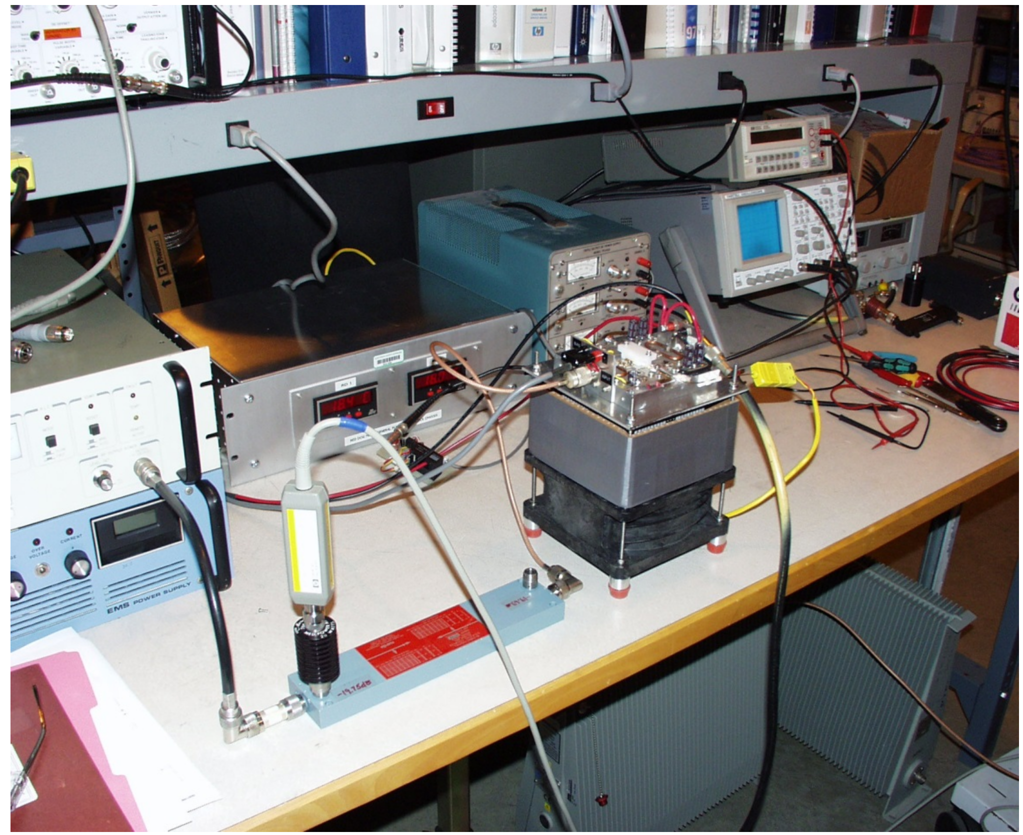


Initial Tests of the Freescale MRF6VP41KHR6 Device

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

- **Duty factor was increased to 50%**
  → *the transistor survived,* but
  passive components in the
  output network overheated





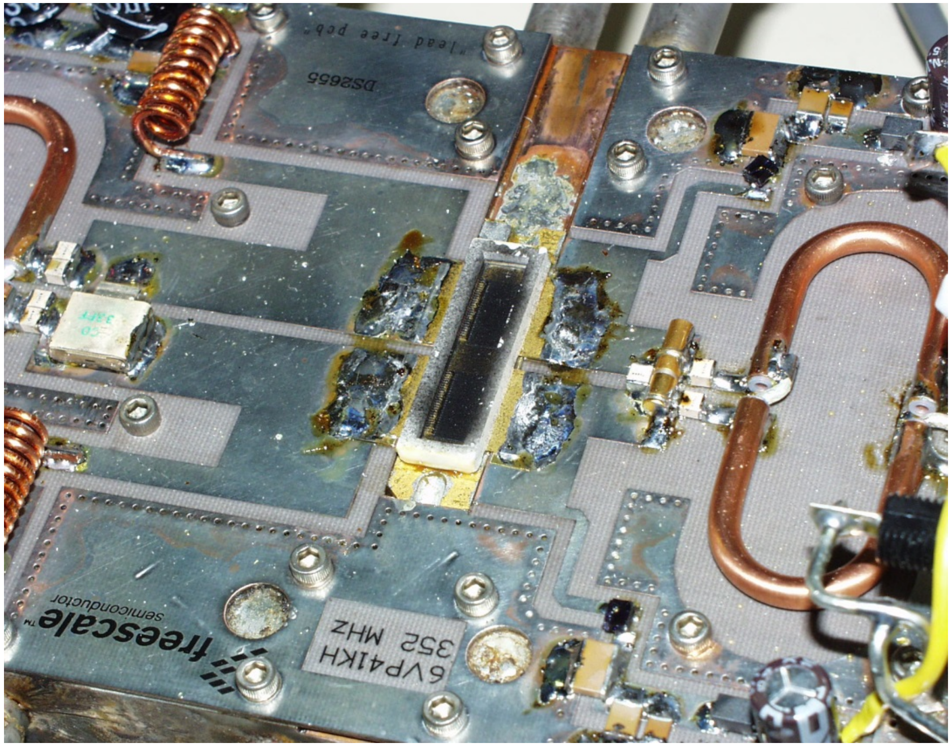
Amplifier test setup showing
forced-air cooling of “pin fin” heat sink

Initial Tests of the Freescale MRF6VP41KHR6 Device

→ Freescale tested a water-cooled MRF6VP41KHR6 device under CW conditions and demonstrated 1kW CW output power at 352.21MHz

- APS built two MRF6VP41KHR6 352-MHz/1kW evaluation boards using "de-lidded" transistors to allow direct measurement of die temperature

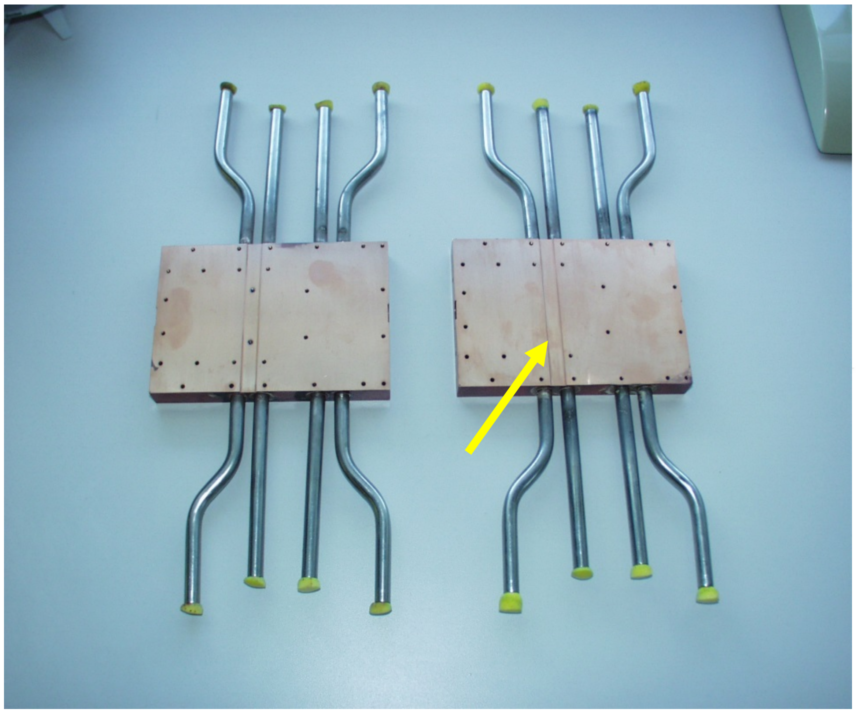
- APS designed a copper cold plate for improved cooling efficiency

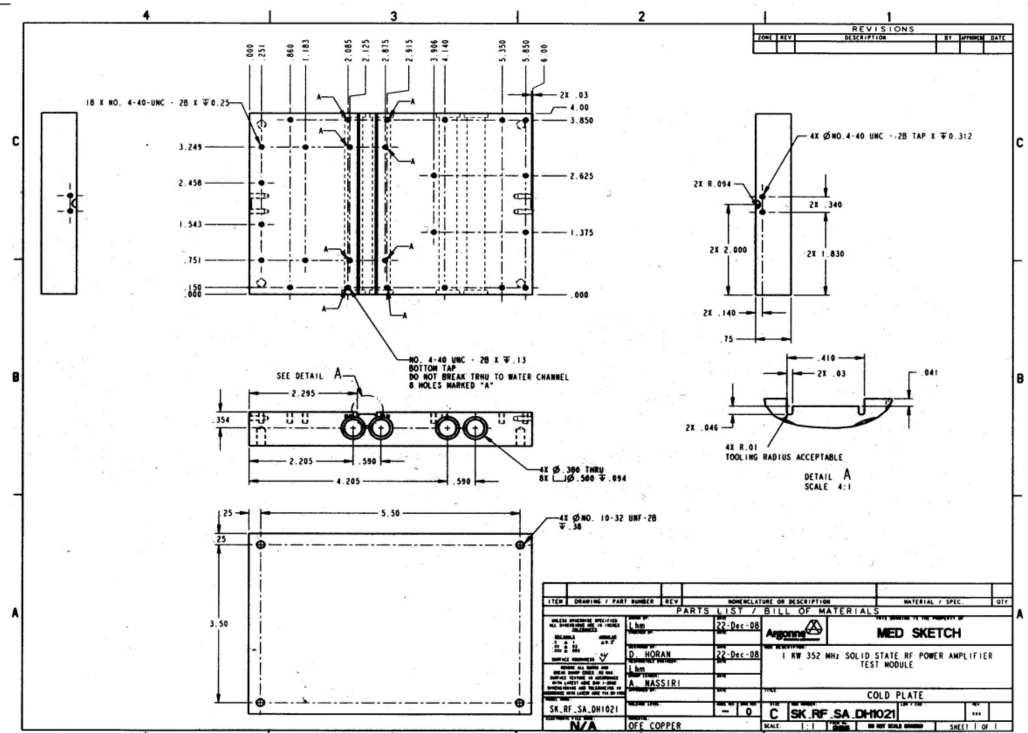


Test amplifier with "de-lidded" transistor

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

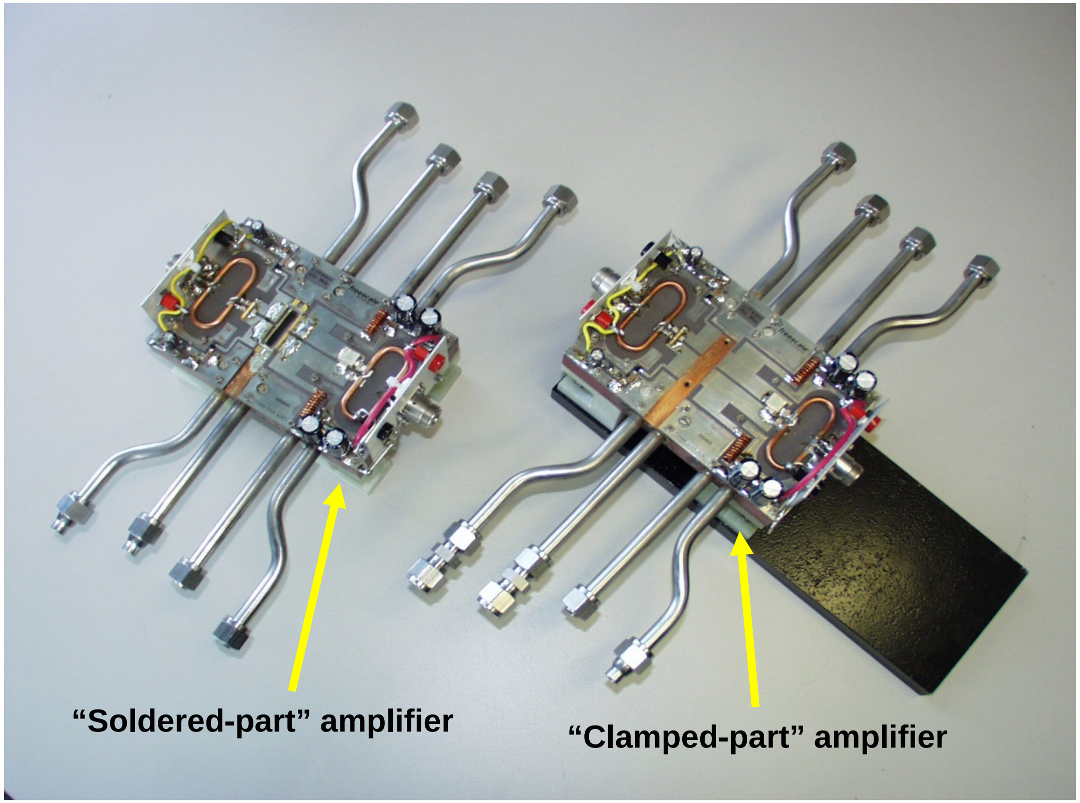
→ "Soldered-part" cold plate has no transistor mounting holes…..transistor is soldered directly to the cold plate

352MHz 1kW Amplifier Construction

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

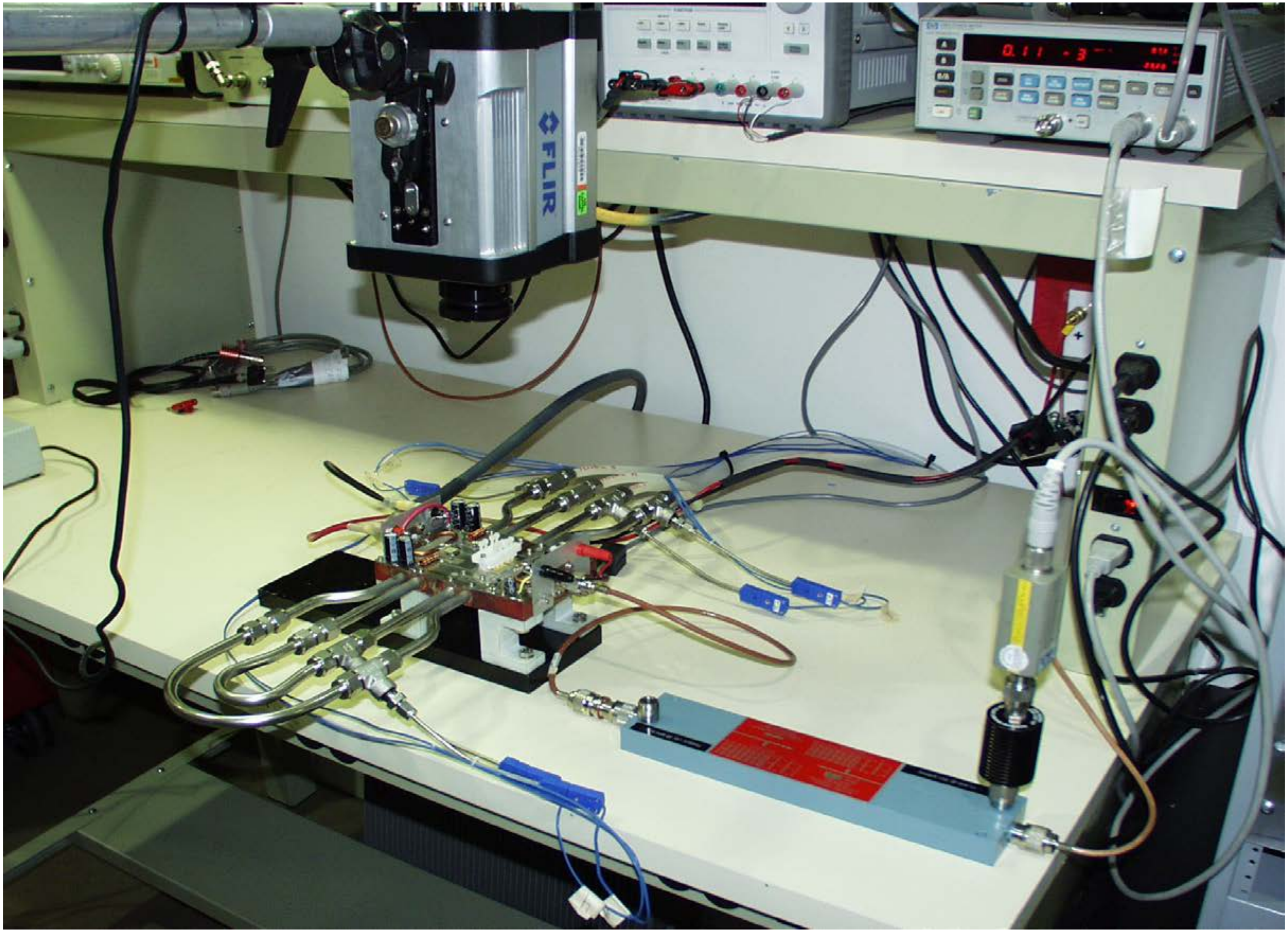
→ *Assembly soldering had to be done in stages using a hot plate and a 200-watt soldering iron*

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



COMPLETED AMPLIFIERS

352-MHz 1kW CW Amplifier Test System and Plan



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

→ **Vd = 49.46V**

→ **Id = 29.06A**

→ **Idq ≈ 150mA**

→ **Pdc input = 1437.3 watts**

→ **Efficiency = 63.2%**

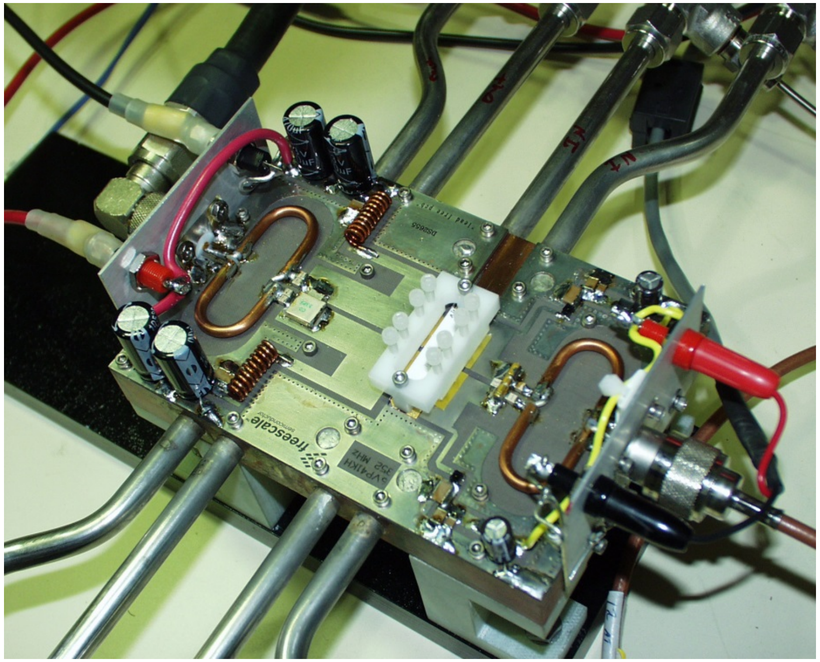
→ **RF output ≈ 909 watts (derived from water calorimetric power calculation)**

→ **RF input = 8.53 watts**

→ **Input return loss = 10.3dB**

→ **RF gain ≈ 20.2dB**

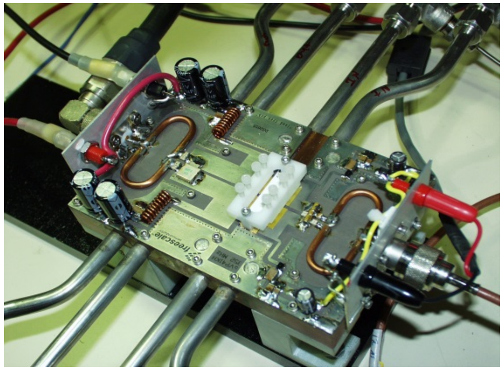
→ **Water thermal power = 528 watts**

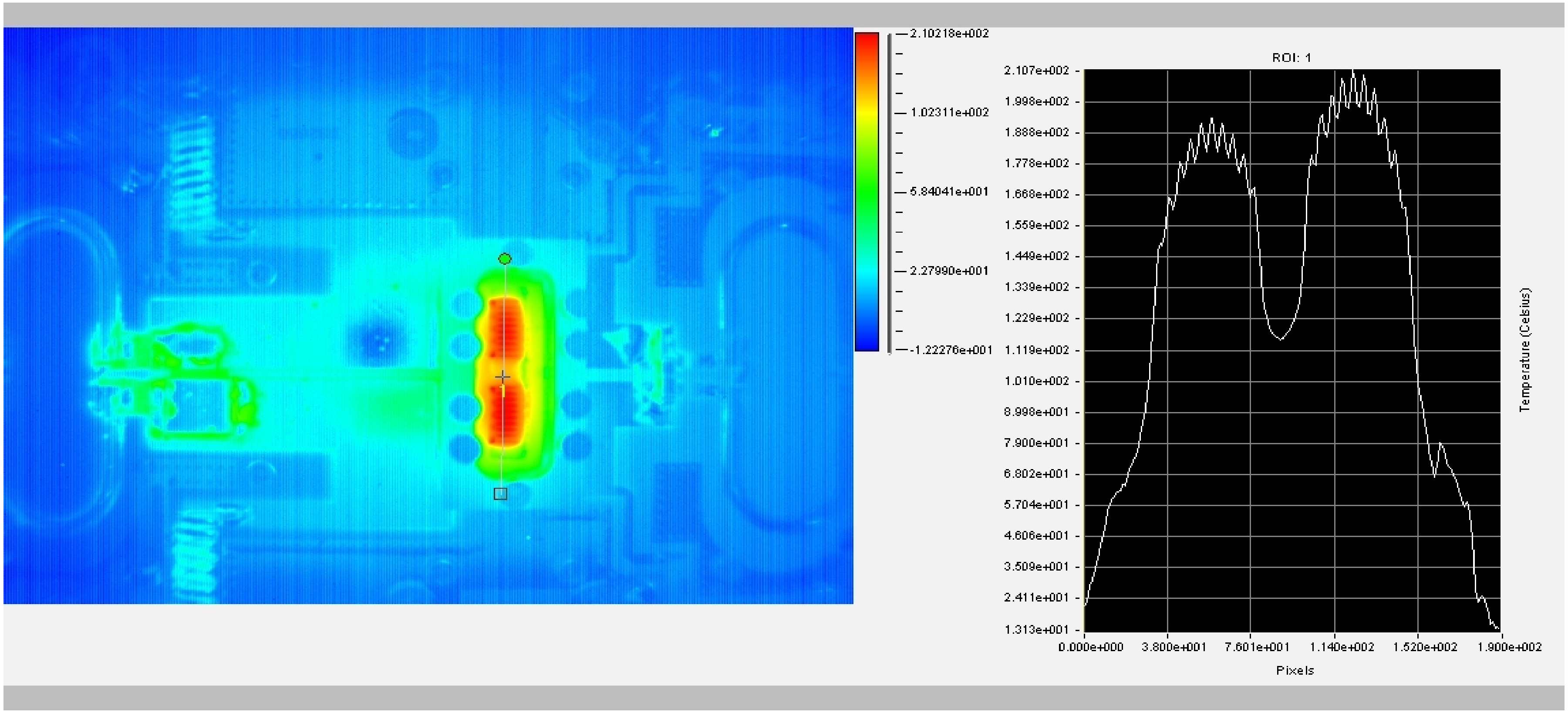


Initial efficiency was abnormally high (69.5%), so rf power meter readout at 1kW was suspect……….rf power was derived from power dissipation in water circuits

352MHz/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

→ Vd = 49.26V

→ Id = 30.65A

→ Idq ≈ 150mA

→ Pdc input = 1509.82 watts

→ Efficiency = 66.2%

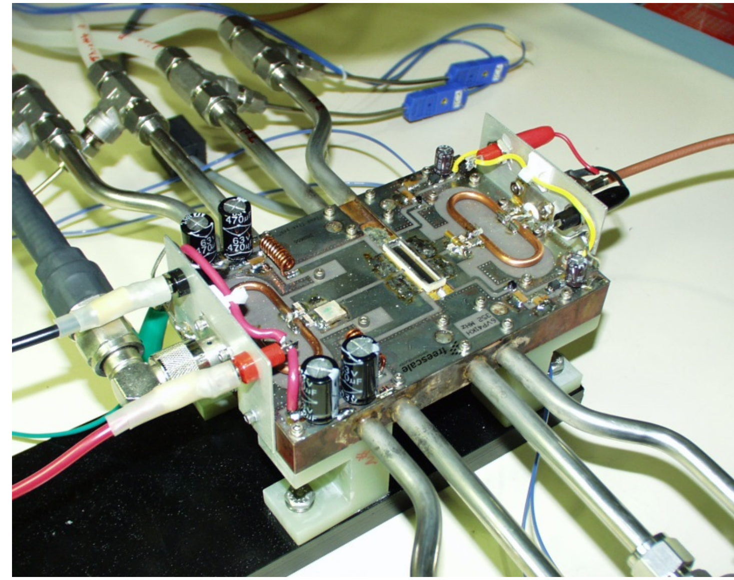
→ RF output = 1000 watts

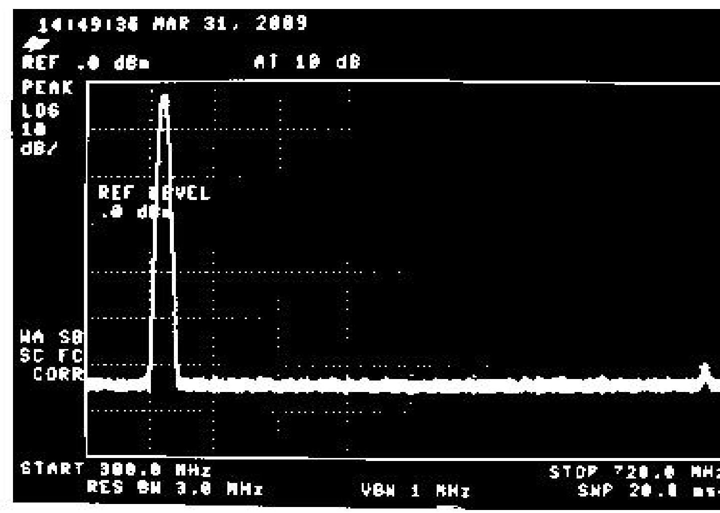
→ RF input = 8.32 watts

→ Input return loss = 10.07dB

→ RF gain = 20.79dB

→ Water thermal power = 572.8 watts

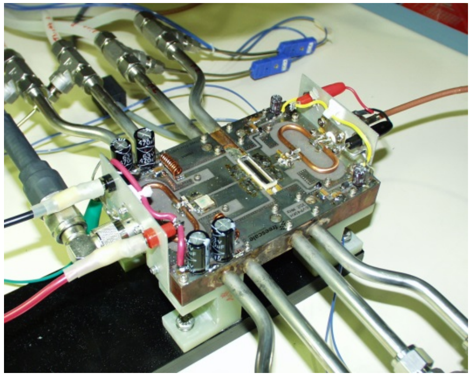


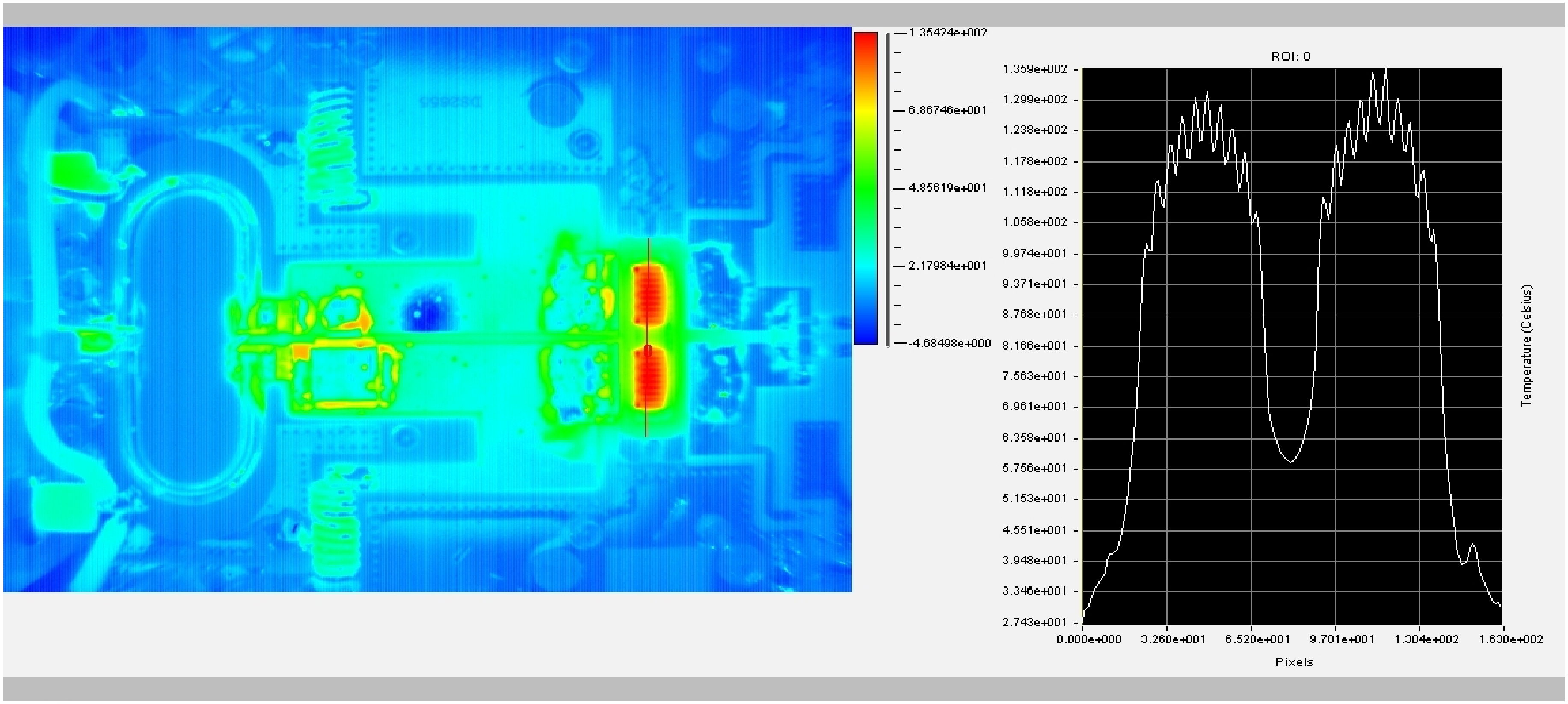


352-MHz 1kW CW "Soldered Part" Amplifier Test Results

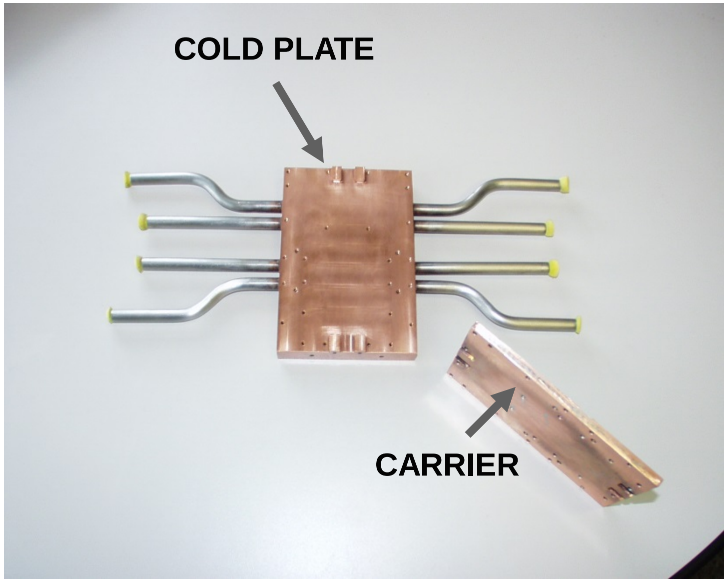
- **Maximum die temperature was 136ºC at 1kW output –** ***translates to a device MTTF of ~ 9E+6 hours.***

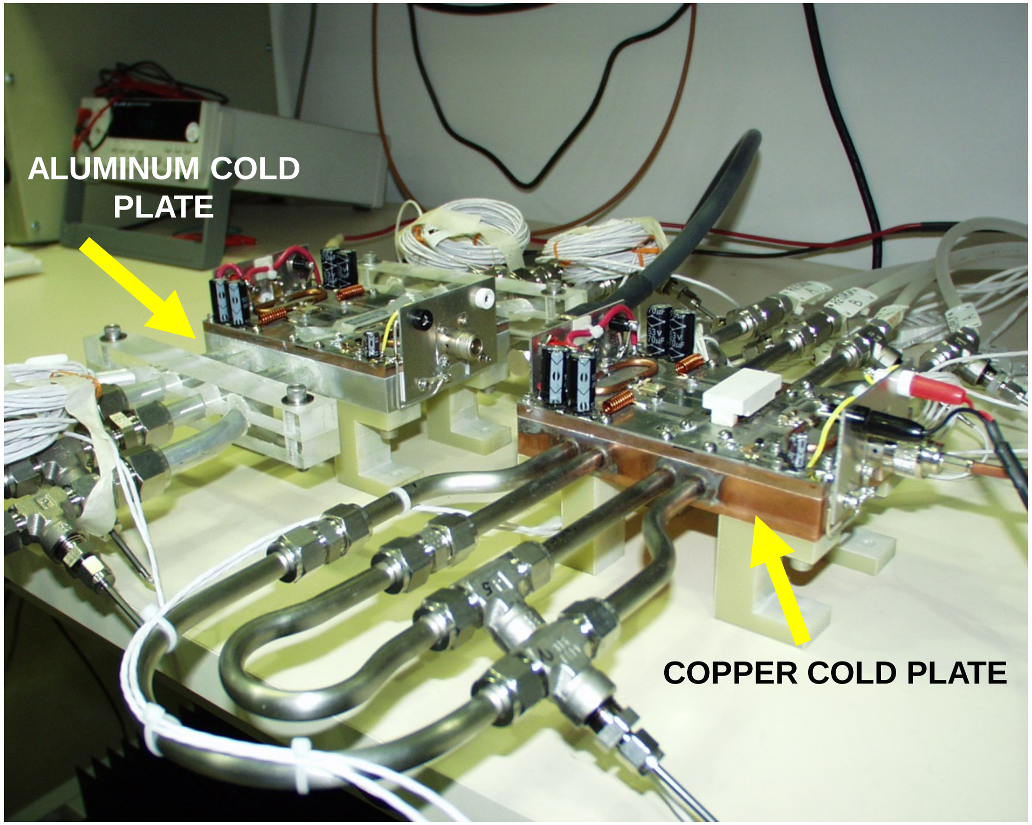
- **Temperature on top of flange between dies ≈ 58ºC**





Construction of “Carrier-Cold Plate” Amplifiers



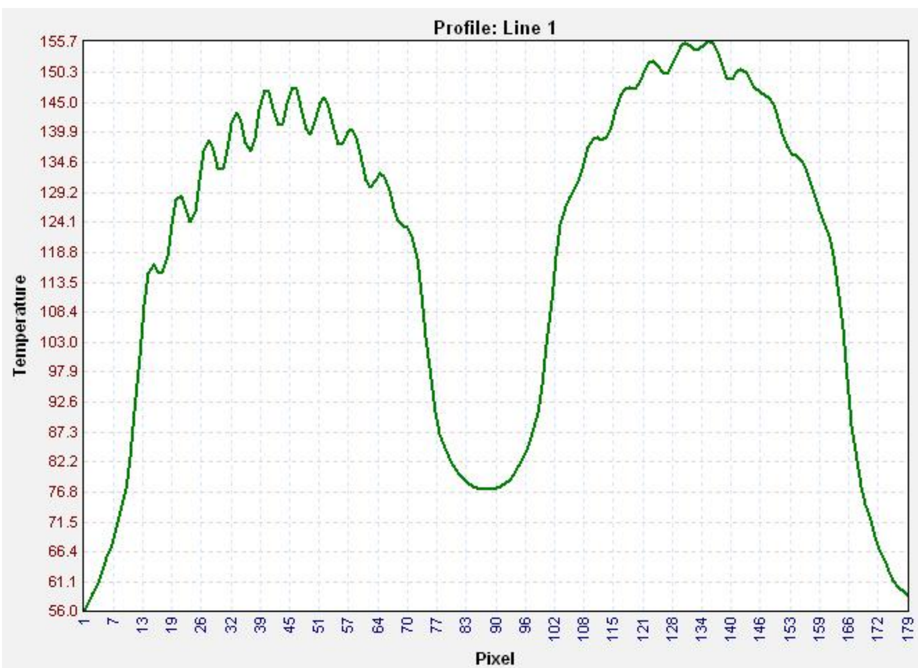


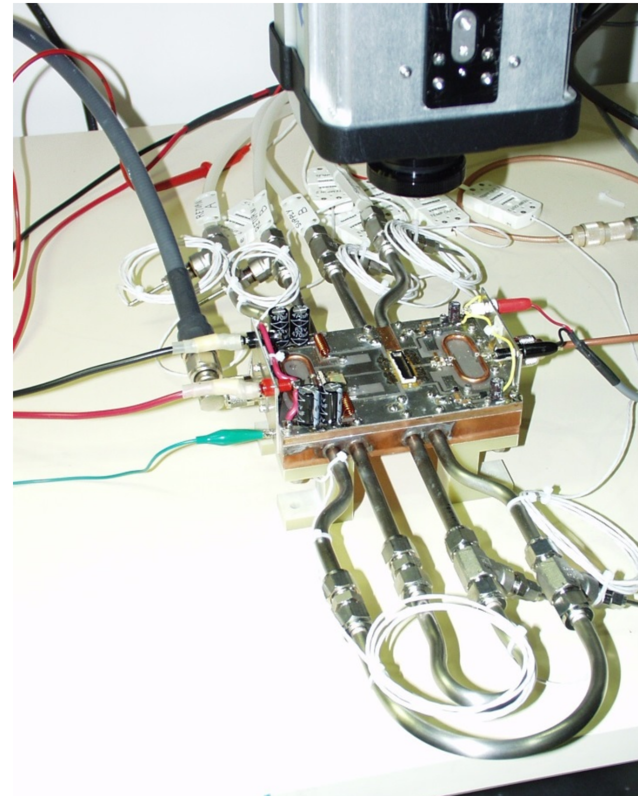
- **Amplifier circuit board soldered to 0.25” carrier**
- **Carrier attached to cold plate by screws, using thermal grease for heat transfer**
- **Aluminum and copper cold plate built and tested**

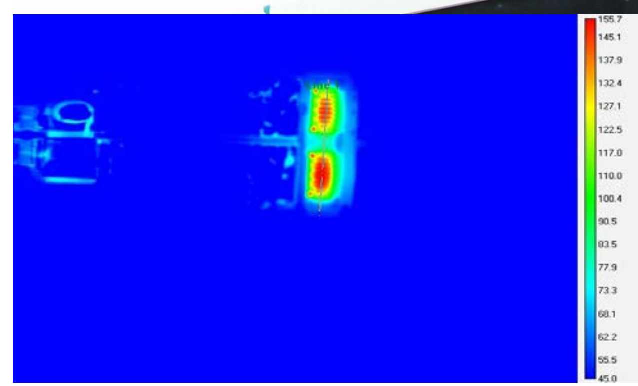
Testing of Copper Cold Plate Amplifier

- **Maximum die temperature at 1,012 watts output was 155.7°C**

- **69.6% efficiency**

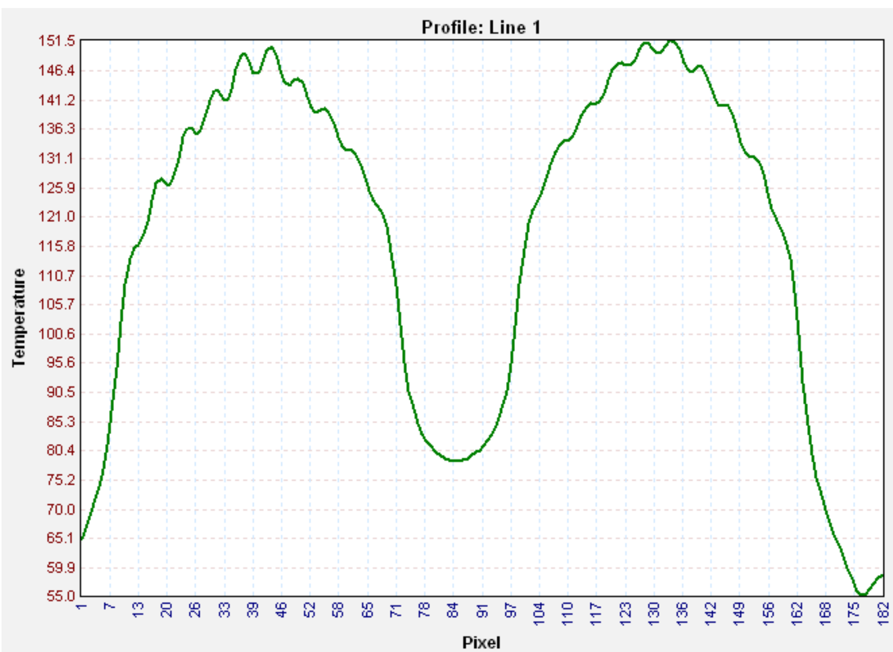


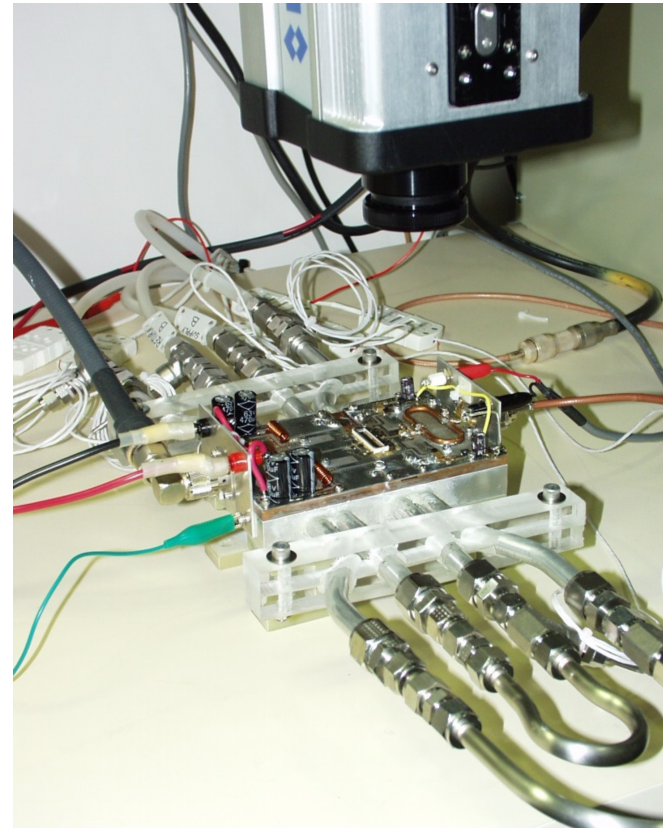


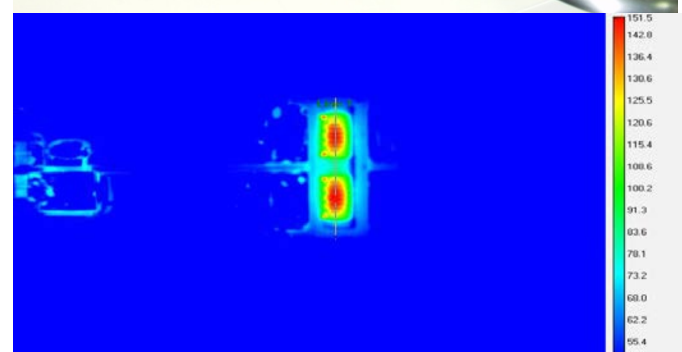


Testing of Aluminum Cold Plate Amplifier

- **Maximum die temperature at 1,010 watts output was 151.5°C**
- **70% efficiency**

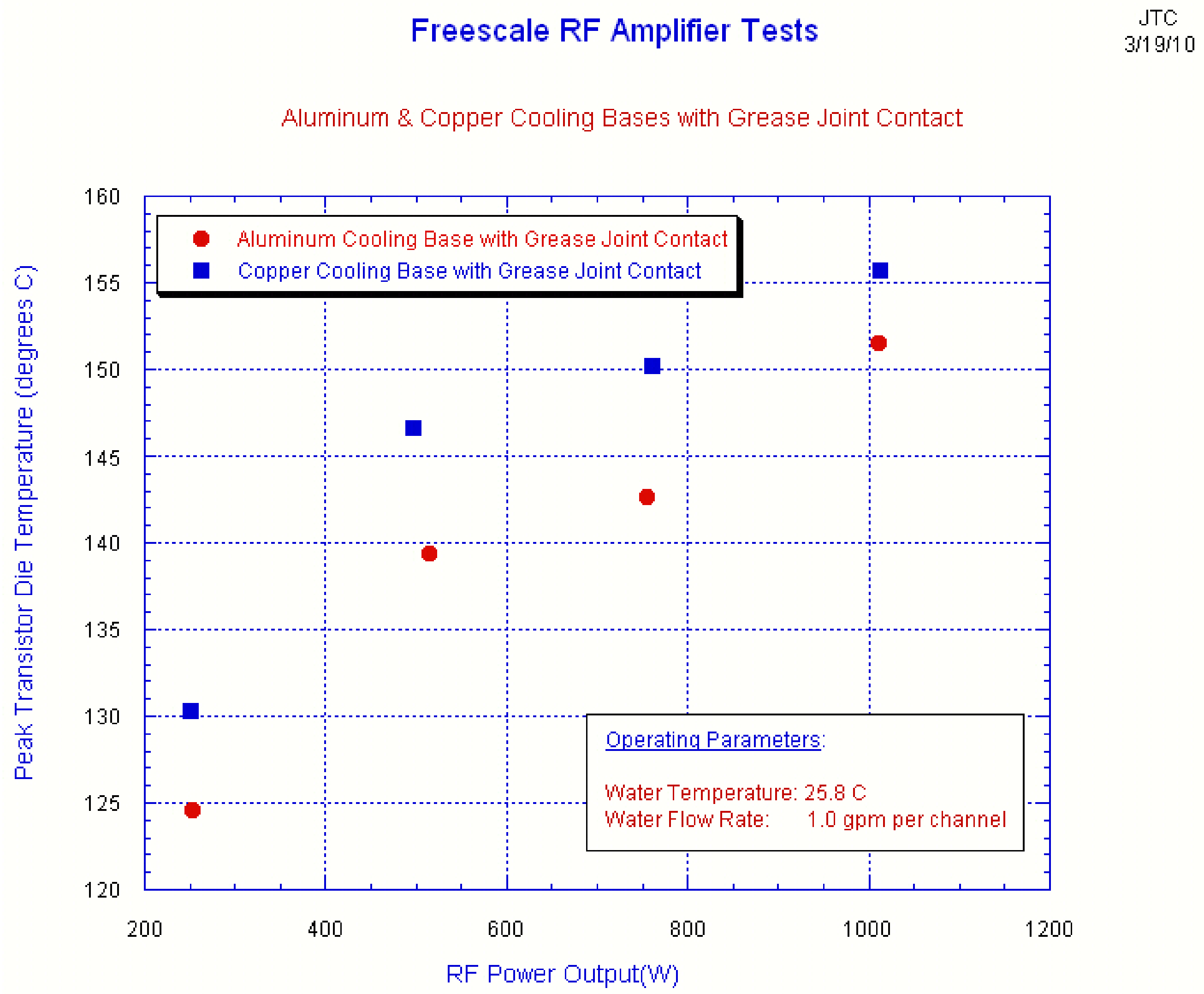






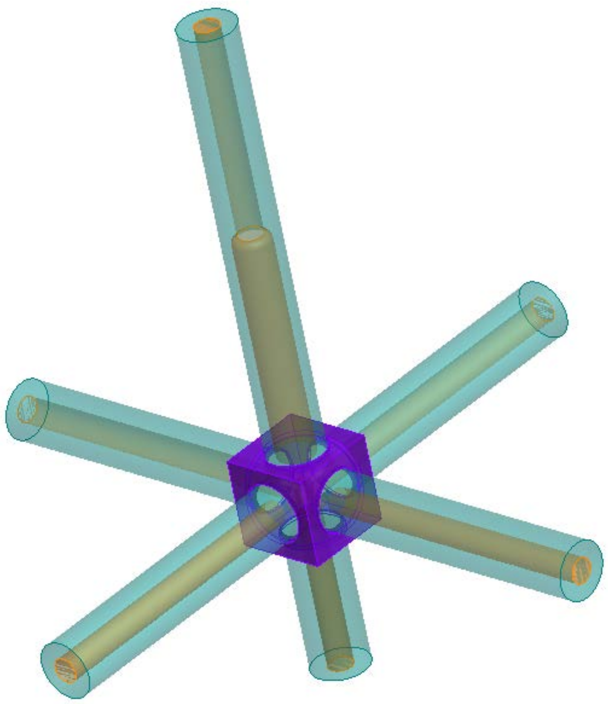
Thermal Performance of Aluminum and Copper Cold Plates

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

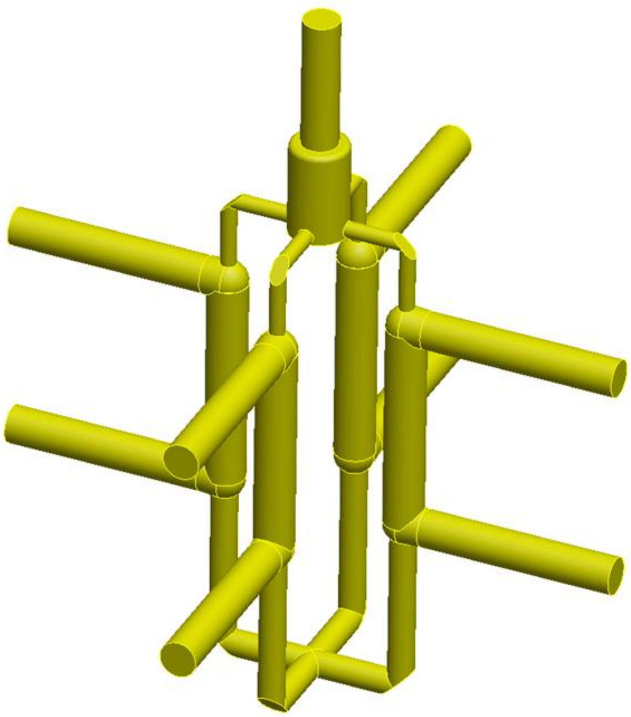


Design of Quarter-Wave 4-Way Combiner

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

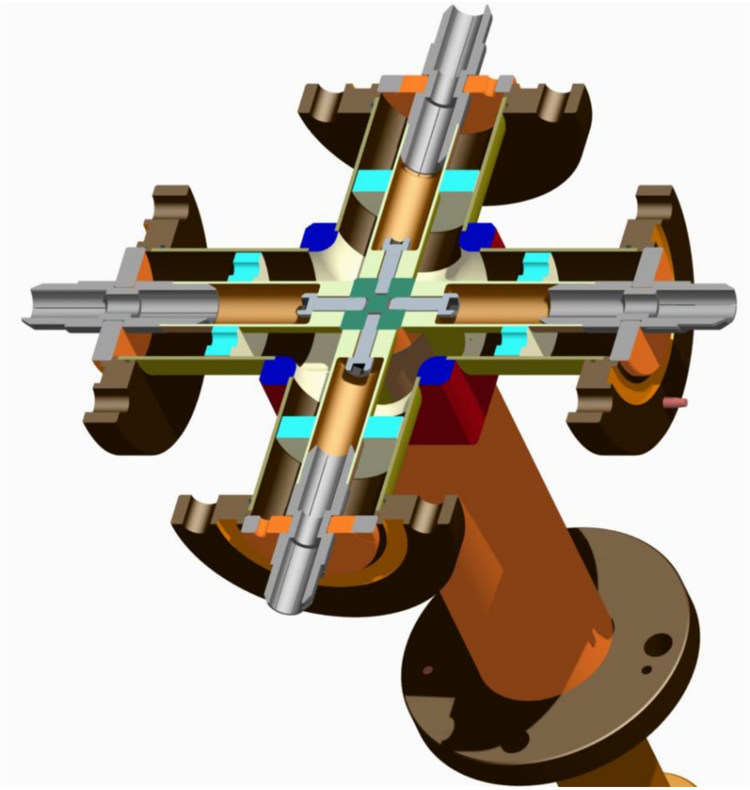


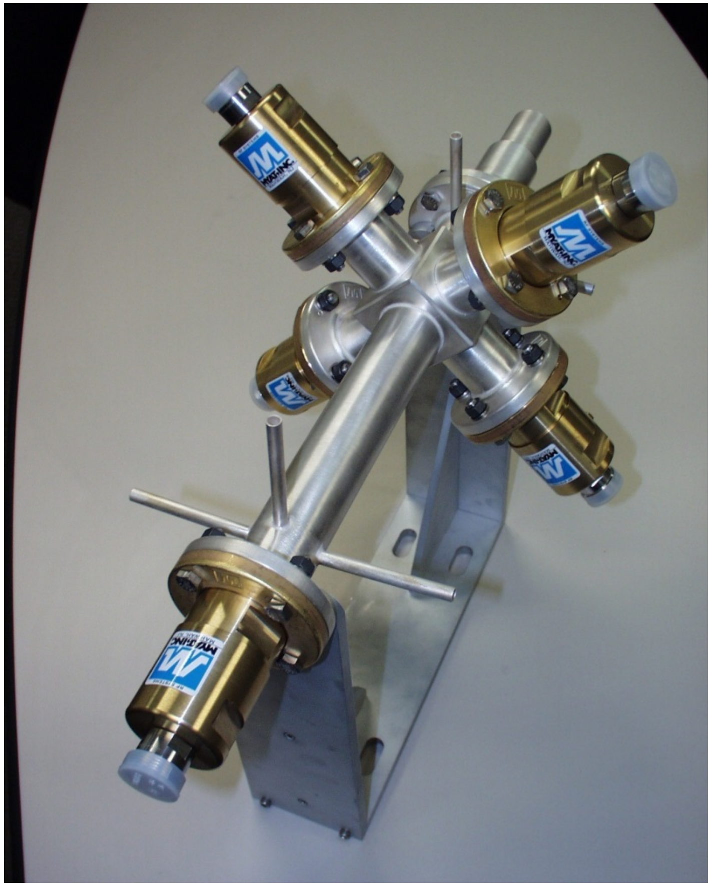
Standard quarter-wave coaxial combiner



Gysel Combiner

Design of Prototype Quarter-Wave 4-Way Combiner

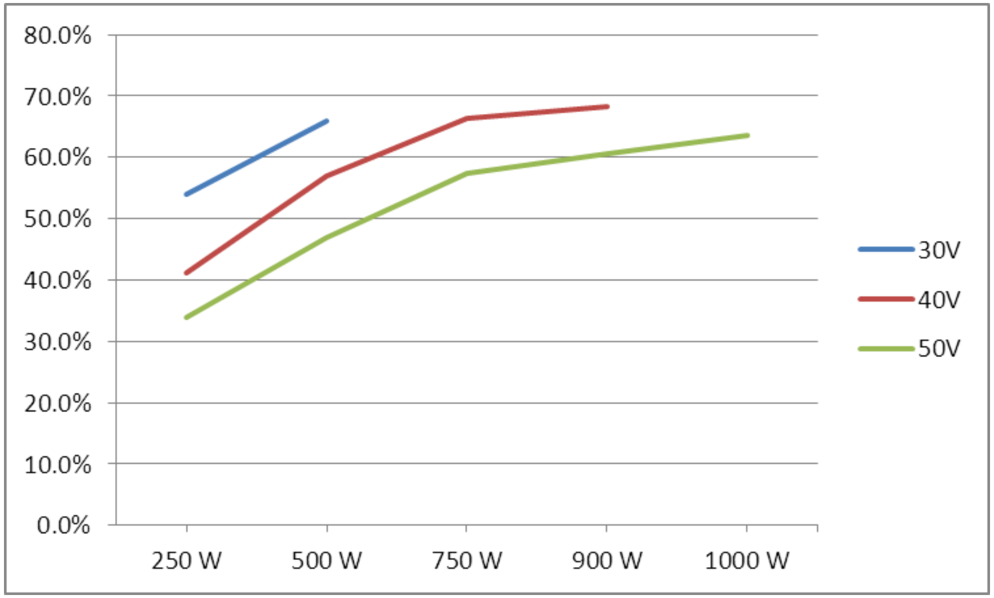


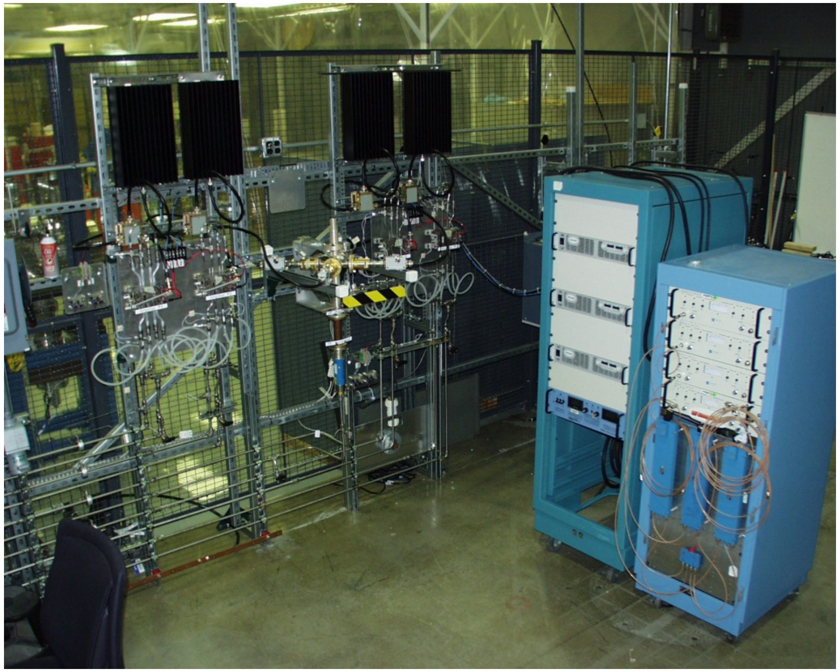


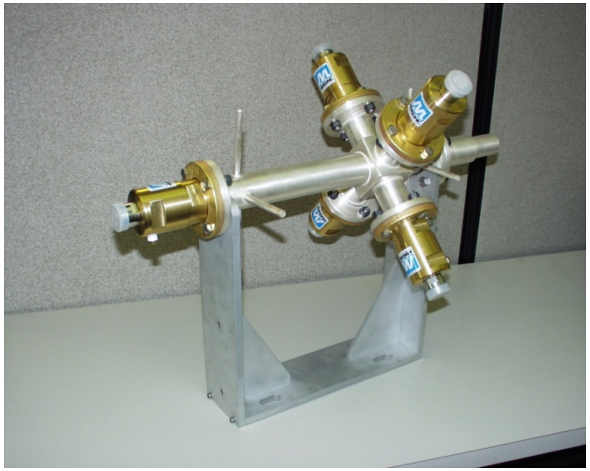
- **Constructed with 1-5/8" EIA standard coaxial components**
- **Utilizes sliding shorting plunger for tuning**

APS 352-MHz 4kW Demonstration

- **Produced 3.45kW CW**
- **Used drain voltage control to improve efficiency at intermediate power ranges**





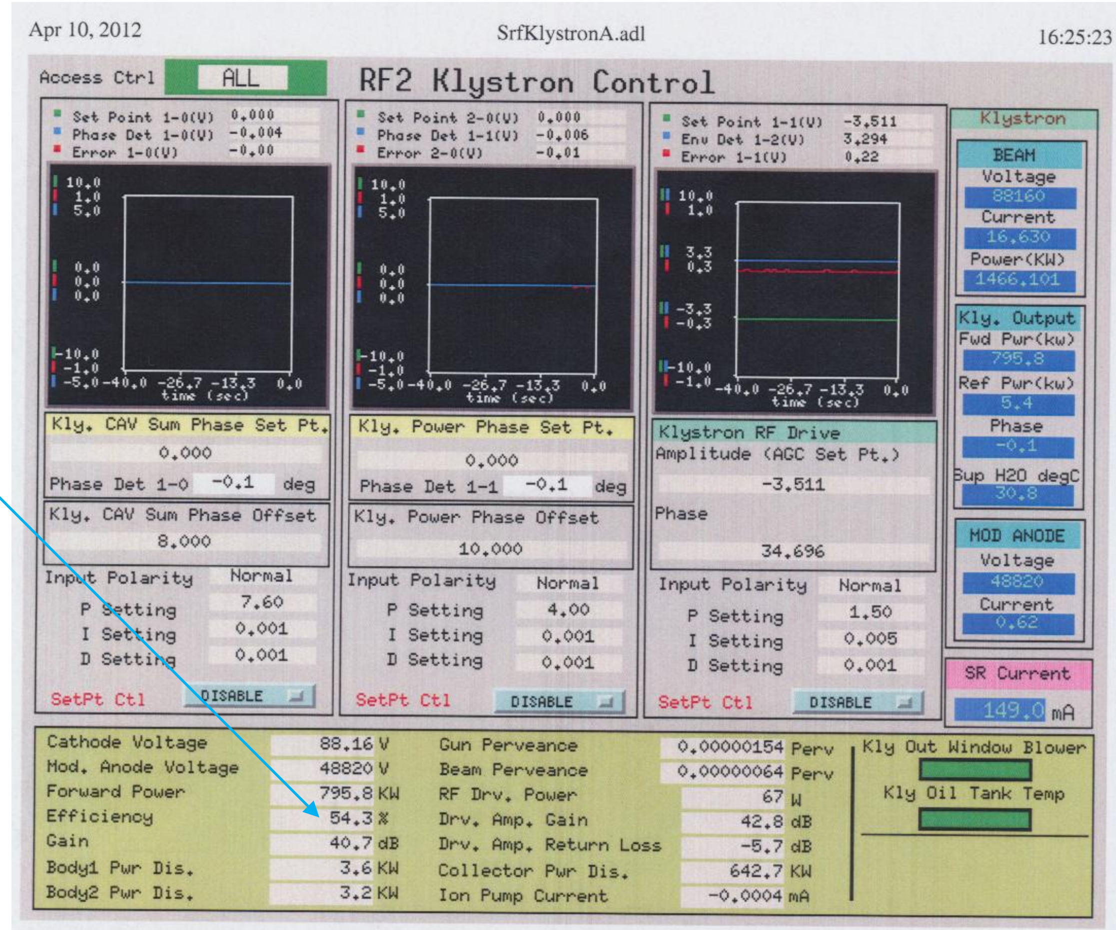


Why Consider Solid State RF Power for APS?

- **Improved operating efficiency?** – *yes*
- **Improved reliability?** – *not so sure*
- **Lower maintenance costs?** – *probably*
- **Cleaner rf power?** – *yes*
- **Availability of 352-MHz/1MW CW klystrons?** – **…**???

Improved Efficiency

- **SR RF system efficiency poor (≈ 30%) at injection**
  → ≈ 350kW klystron rf output
- **Improves to ≈ 55-60% with 150mA stored beam**
- **Booster efficiency is *very poor* due to low average rf power, ≈ *16%***



A solid state amplifier system with efficiency optimization could improve average storage ring rf system efficiency by ≈ 10-15%............ *But a 200kW IOT could do it too*

APS RF System and Facility Reliability

- **RF downtime and Mean Time To Fault (MTTF):**

  → FY2010: 0.31% -- 307.8 hours

  → FY2011: 0.10% -- 490.6 hours

  → FY2012: 0.16% -- 828.2 hours

- ***Latest run, Feb 1, 2013 to April 25, 2013:***

  → RF downtime and MTTF: *0.31% -- 853.8 hours*

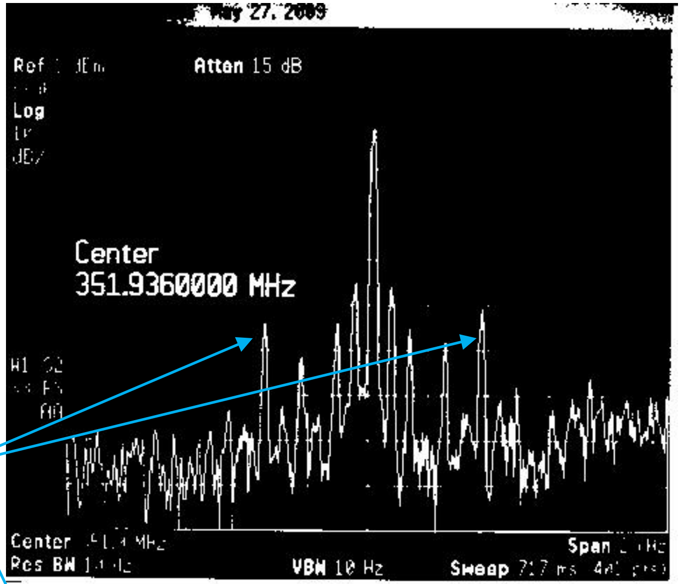
  → *APS downtime and MTTF: 1.14% --170.8 hours*

No klystron-related downtime since 2011

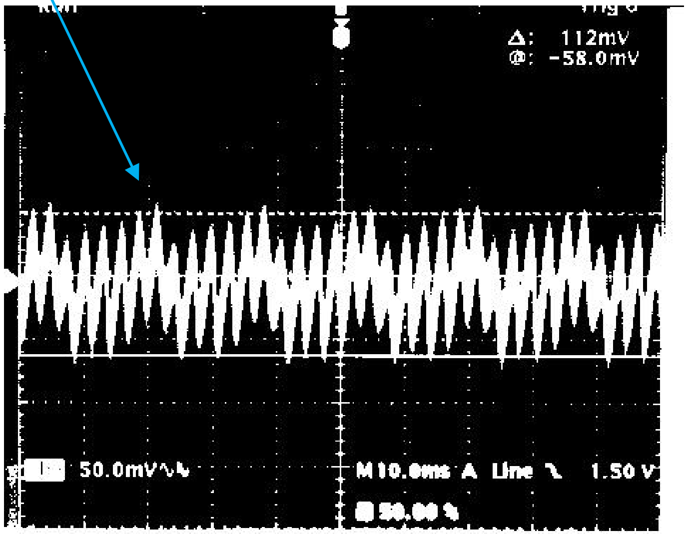
Cleaner RF Power

- The APS Short Pulse X-Ray (SPX) Upgrade will require a significant reduction in phase and amplitude noise on the storage ring rf
- The major source of noise has been identified as 360Hz and other ac line harmonics on the klystron HVPS output
- LLRF Adaptive feed-forward compensation techniques are being developed to address the problem in the present rf systems………..

The 352-MHz/1kW solid state amplifiers tested at APS have demonstrated very low uncorrected noise



360-Hz HVPS RIPPLE SIDEBAND



360-Hz HVPS RIPPLE, ~ 900v p-p

352-MHz/1MW CW Klystron Availability

- **Presently only one supplier with an existing design**
- **Cost per unit increased by ≈ 300% since 1992**
- **The number of operating sockets worldwide for these klystrons is shrinking**
- **Other capable suppliers exist, but NRE would be significant**

APS 352-MHz Klystron Inventory

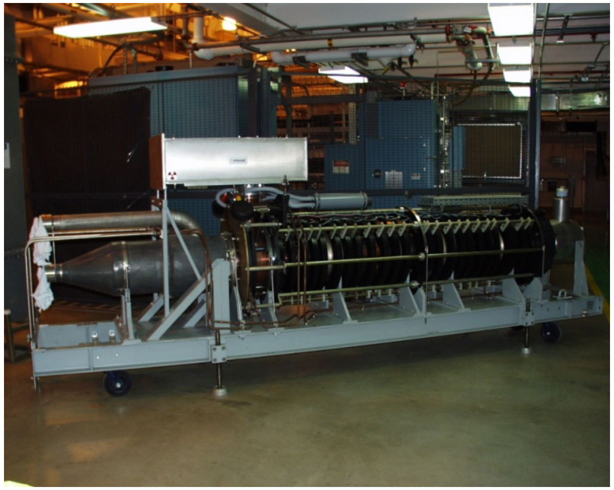
- **Operating klystron hours as of May 15, 2013:**

  → ***RF1 ---- Thales s/n 089043 ---- 18,097 hr***
  → ***RF2 ---- Thales s/n 089036 ---- 20,650 hr***
  → ***RF3 ---- EEV s/n 01 -------------- 78,950 hr***
  → ***RF4 ---- Thales s/n 089030 ---- 50,303 hr***
  → ***RF5 ---- Thales s/n 089026 ---- 68,998 hr***

- **Average klystron lifetime at APS is ≈ 36k hours***

- **Higher output power required for 150mA operation will shorten lifetime**

*** Includes all failures and end-of-life retirements since start of APS operation → 6,139 hrs (shortest) to 77,275 hrs (longest)**



APS 352-MHz Klystron Spares

- → ***Thales s/n 089024 ---- rebuilt, FAT on Aug. 30, 2004***
- → ***Thales s/n 089029 ---- rebuilt, FAT on Dec. 8, 2003***
- → ***Thales s/n 089033 ---- rebuilt, FAT on Feb.6, 2007***
- → ***Thales s/n 089048 ---- new, tested at APS***
- → ***Thales s/n 089054 ---- new, tested at APS***
- → ***Thales s/n 089055 ---- new, tested at APS***
- → ***E2V s/n 01 ------ Used, retuned, tested to 1MW, June 10, 2011***
- → ***E2V s/n 005 ---- Used, retuned, tested to 1MW, June 10, 2011***
- → ***Philips s/n 73201.55 ---- Used, retuned, tested to 1MW, Feb 10, 2011***

Retired klystrons that still function:

- → ***Thales s/n 089041 --- retired May 3, 2010 at 56,360 hours (sideband instabilities, high body losses, x-rays)***
- → ***EEV s/n 01 ------------- retired Jan.11, 2012 at 77,725 hours (no issues)***

Do we have enough spares to last APS lifetime?

Solid State Challenges at APS

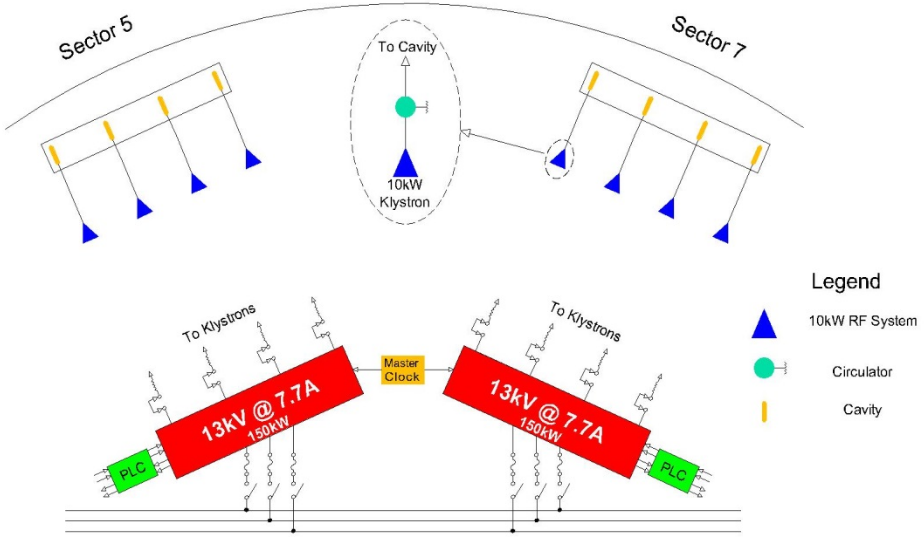
- **Cost**
  → The cost of solid state power, plus reconfiguring 352-MHz rf topology to one 200kW amplifier per cavity (x12 or 16) would require a complete redesign of waveguide, LLRF, ac power, water, and interlock systems *– even at $5/watt for SS power, the total cost could exceed $30-$40M*

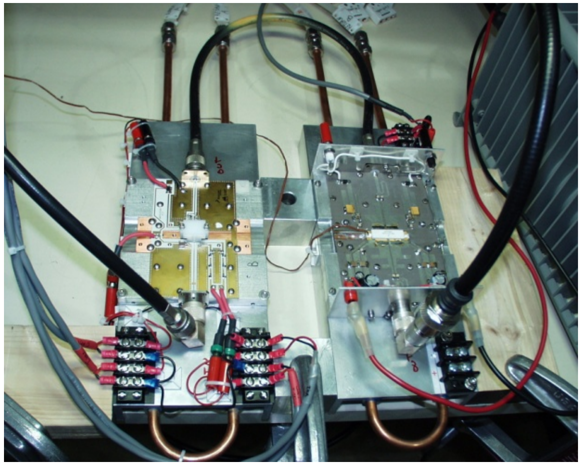
- **Physical Constraints**
  → Existing klystron rf systems produce ≈ 950 watts per sq-ft of floor space……..*a solid state system must fit in the existing building*

- **Interruption of APS Operations**
  → Reconfiguring 352-MHz HLRF topology alone would require significant dark time

APS Upgrade – SPX → Short Pulse X-Ray

- **Eight superconducting S-band deflecting cavities**
- **SPX preliminary design calls for 10kW cw power per cavity at 2.815GHz using klystrons**
- **10kW cw at S-band is possible with solid state**
- **Power -vs- cost break point between solid state and existing klystrons appears to be at ≈ 3-4kW cw**
- **SPX S-band cw power costs estimated at ≈ \$55/watt for solid state and ≈ \$20/watt for klystrons**

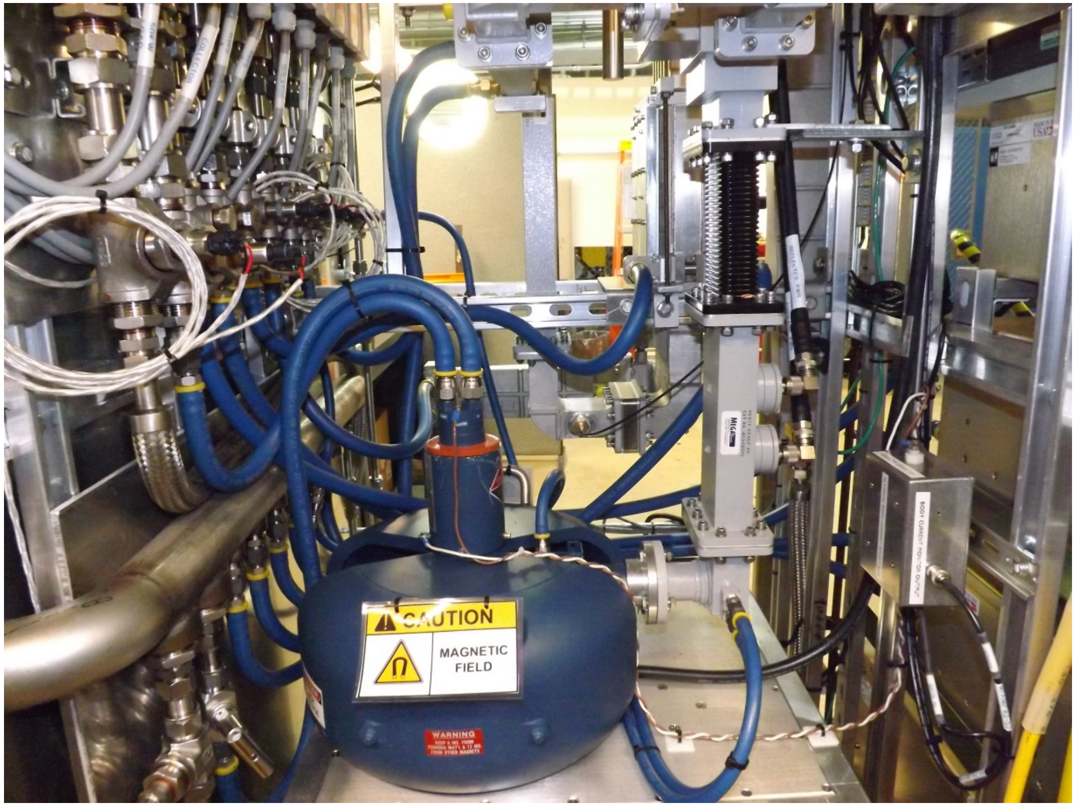




SOLID STATE 2.815GHz/150 WATT CW DEMONSTRATION AT APS

L-3 2.815GHz/5kW CW Klystron For SPX R&D (SPX0)

- **1-5/8" EIA coaxial output**
- **Permanent magnet focus**
- **Mod-anode gun, but will be operated in diode mode**
- **Requires 12kV @ 1.3A**
- **RF gain ~ 42dB**
- **Efficiency only ≈ 32%, *but no focus supply needed***
- **Stable operation to full power**

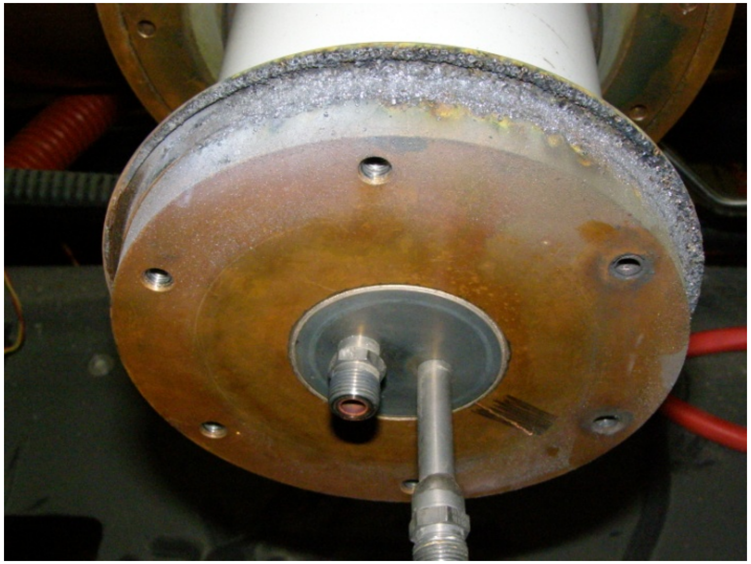


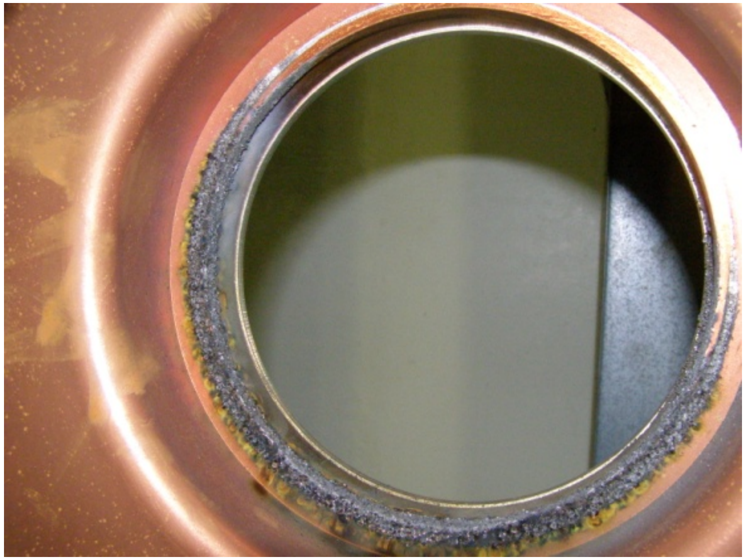
5kW KLYSTRON SHOWN IN POSITION INSIDE SPX0 AMPLIFIER CABINET

SPX0 2.815GHz/5kW CW Amplifier System

- Utilizes L-3 L4442 PM-focus klystron
- 50kW output isolator and internal RF test load
- Includes waveguide shutters between klystron and isolator input port
- Ultra-low ripple HVPS for minimal phase and amplitude noise on output

Recent Hardware Problems at APS
→ *Damaged Booster Input Coupler*





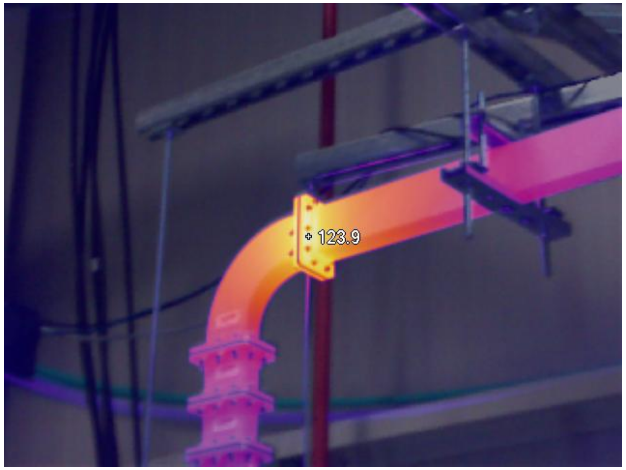
- Arcing at waveguide transition caused by degraded rf contact with waveguide transition matching post
- Coupler had to be replaced after 17 years of service!
- Same problem seen on one other coupler, but not as bad
- One coupler will be disassembled for inspection every shutdown from now on

Recent Hardware Problems at APS

→ *WR284 Waveguide Flange Heating*

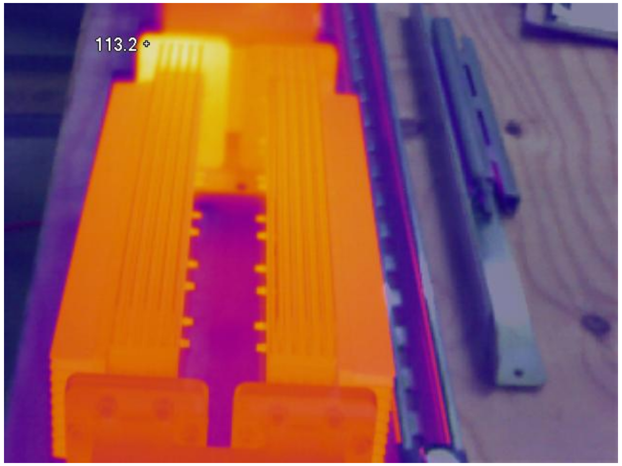
- **Excessive heating at waveguide flanges**
- **Caused by a problem with flange gaskets**
- **The gasket vendor corrected the problem**

→ ***Infrared imaging camera is a valuable troubleshooting tool!***



FLANGE HEATING DUE TO POOR RF CONNECTION
≈ 4kW cw

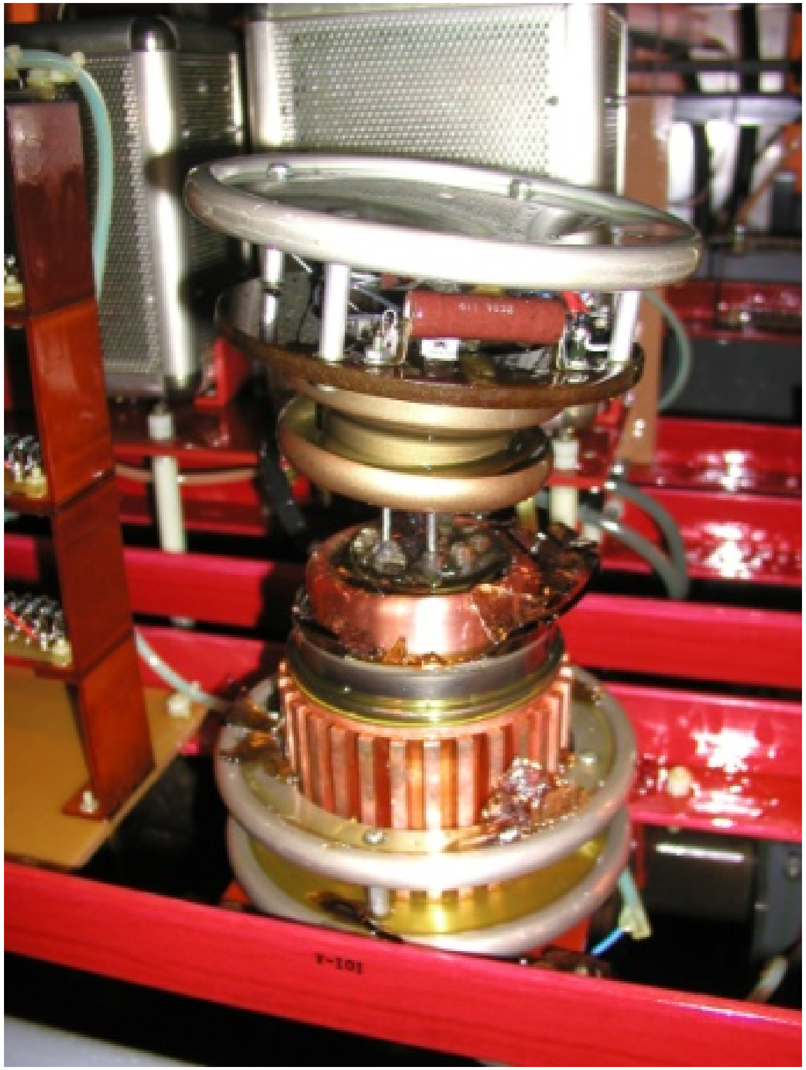
HOT FLANGE BOLT DUE TO IMPROPER TORQUE
≈ 2kW cw



UNEVEN THERMAL PERFORMANCE OF FLANGES ON HOM FILTER
≈ 4kW cw

Recent Hardware Problems at APS
→ *Destroyed TH5188 Tetrode Tube*

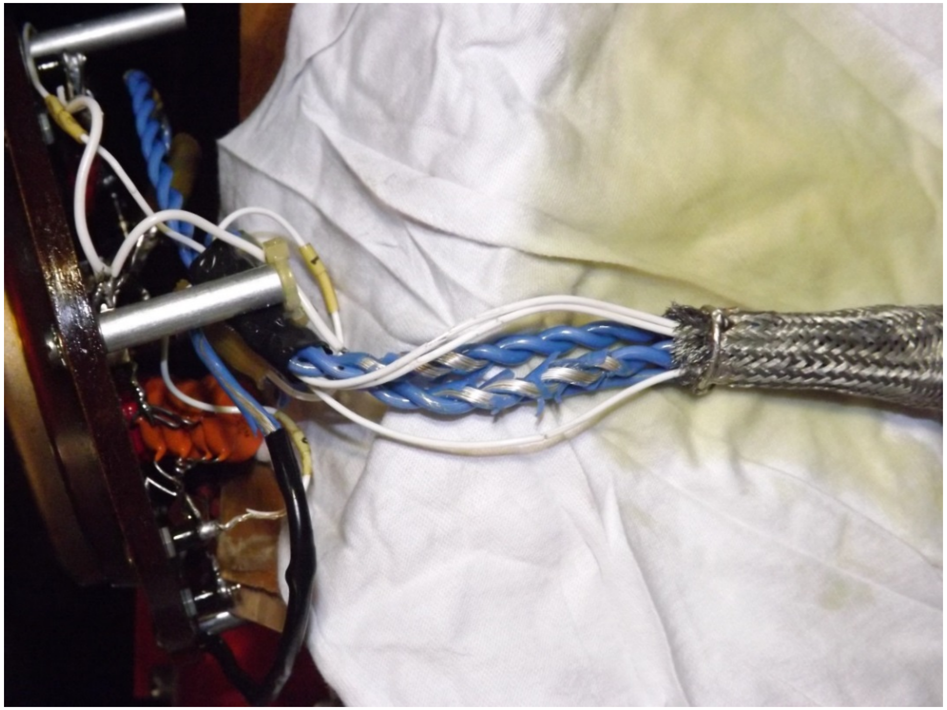
- **Crowbar failed to fire due to accidental disconnection of fiber optic cable**
- **The tetrode took it very hard**
- **Very loud noise, very upsetting to people**
- **On the bright side…….*no other damage occurred***



DESTROYED TETRODE IN HVPS MOD-ANODE REGULATOR TANK

Recent Hardware Problems at APS
→ *Wiring Damage in Klystron Power Supply*

- **Caused intermittent drop-out of klystron mod-anode voltage due to shorts between frayed wiring and shield braid**
- **Long-term exposure to x-rays from tetrode tubes over 18 years of operation is suspected as root cause**
- **All tetrode socket wiring to be replaced**



DAMAGED INSULATION ON WIRING LEADING TO TETRODE SOCKET