Solid State RF Amplifier Development at the Advanced Photon Source

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Outline

- **9.77-MHz Driver Amplifier**
  - → *Application, design requirements and process*
  - → *Construction*
  - → *Performance*
- **352-MHz Amplifier Development**
  - → *Application, design requirements and process*
  - → *Construction*
  - → *Performance*

9.77MHz Design Requirements

- Replacement for original 20-year old obsolete driver amplifiers in accumulator ring rf system

  → *supplies rf drive to grounded-grid triode output stage*

- 9.77MHz operating frequency
- Output 50-500 watts cw
- Use Freescale MRFE6VP61K25 part
- RF gain 25dB minimum
- Forced-air cooling
- Fit into existing enclosures

ORIGINAL DRIVER AMPLIFIER

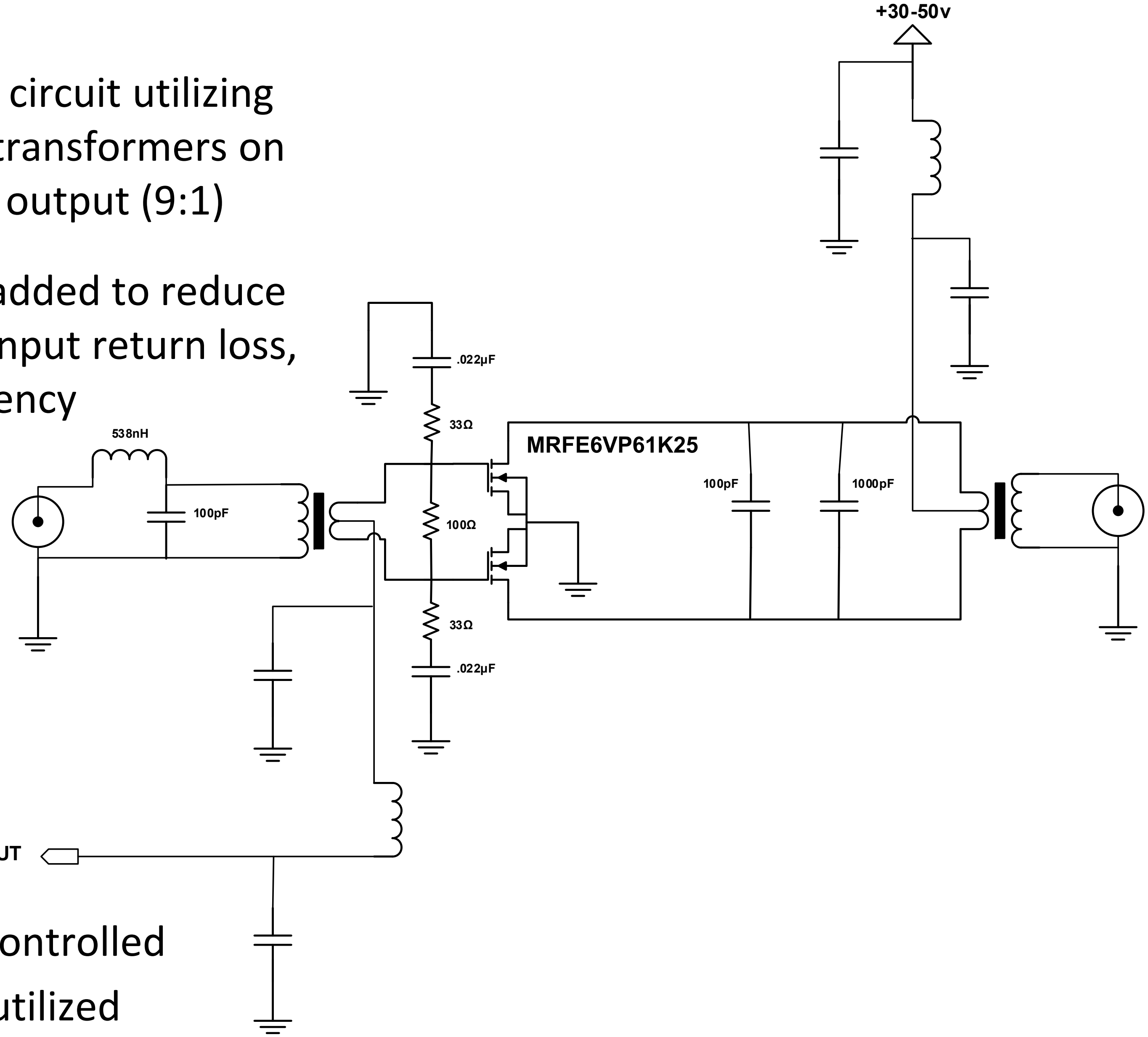
TRIODE POWER AMPLIFIERS

Design Process

- Circuit simulation tools not useful – *accurate model not available for transistor at 9.77MHz*
- Design was "cut-and-try" process, with measurements along the way
- Started with simple circuit, then made modifications necessary to achieve desired stability, gain, and efficiency
- Two prototype units were built: air-cooled and water cooled
- Separate output harmonic filter was designed and tested – *with interesting results*

Basic Circuit

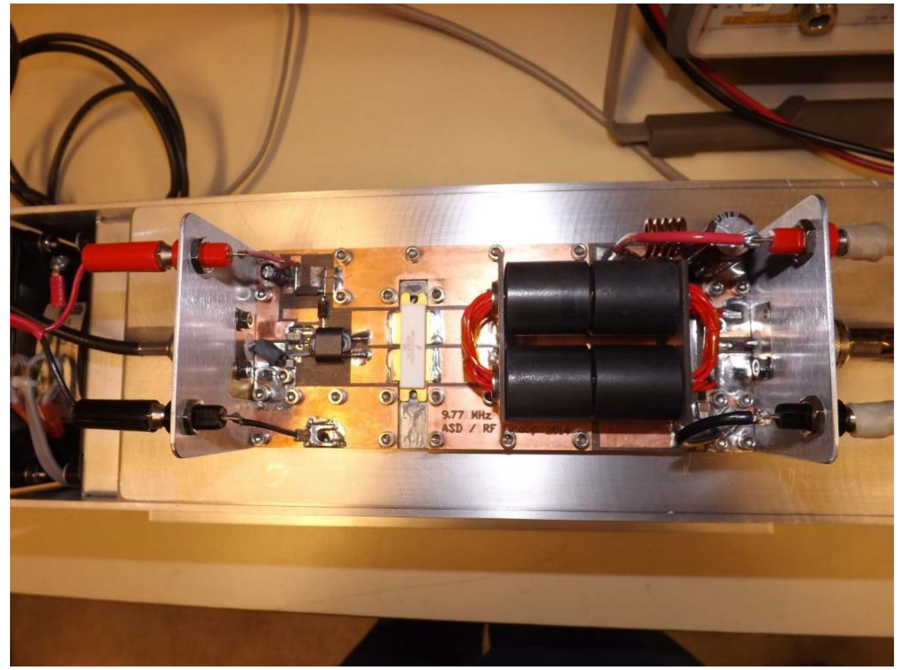
- Basic push-pull circuit utilizing ferrite-loaded transformers on input (4:1) and output (9:1)
- Modifications added to reduce gain, improve input return loss, and peak efficiency

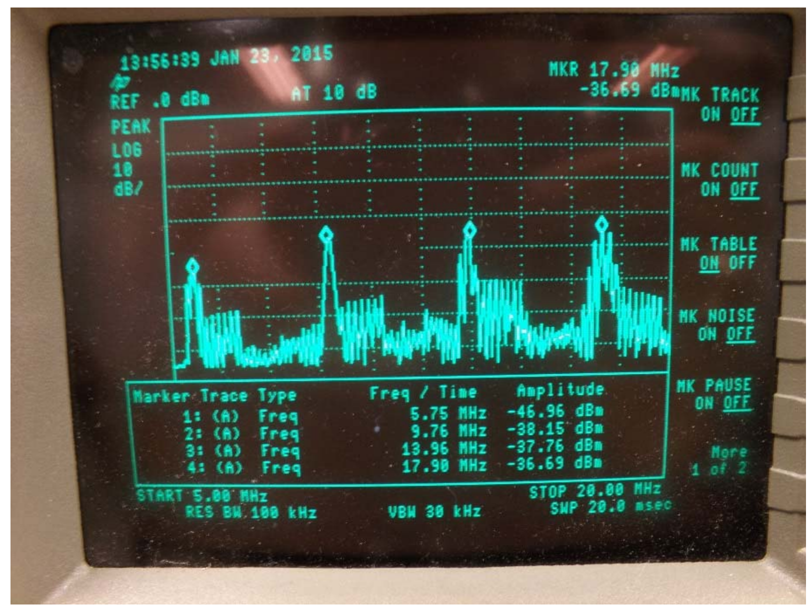


- Temperature-controlled bias regulator utilized

First Prototype Construction and Initial Testing

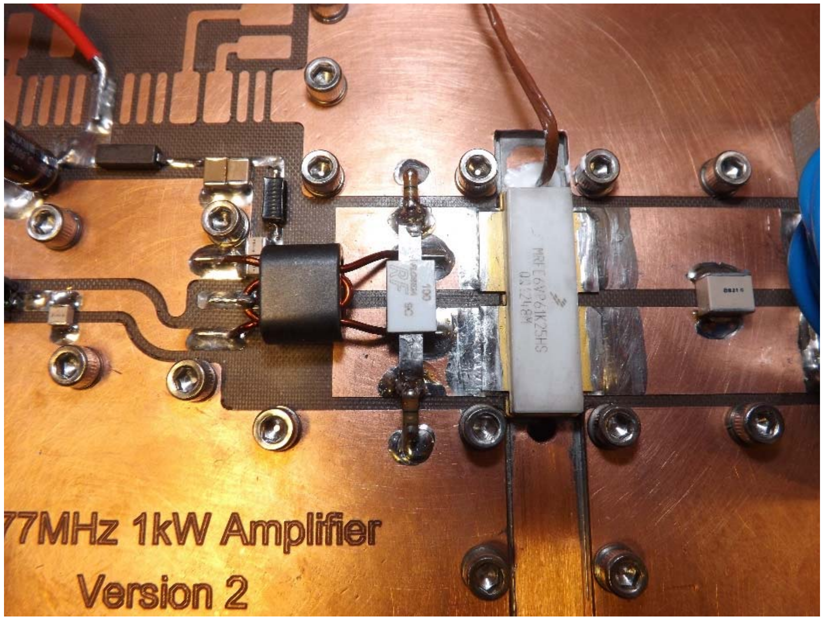
- #61 ferrite cores used in both transformers
- Vd = 45v
- Vg = 2.46v/Idq = 200mA
- RF in = 117mW – gain over 30dB!
- 136 watts rf output
- Input return loss only 5.65dB
- Numerous spurious rf signals seen in output →

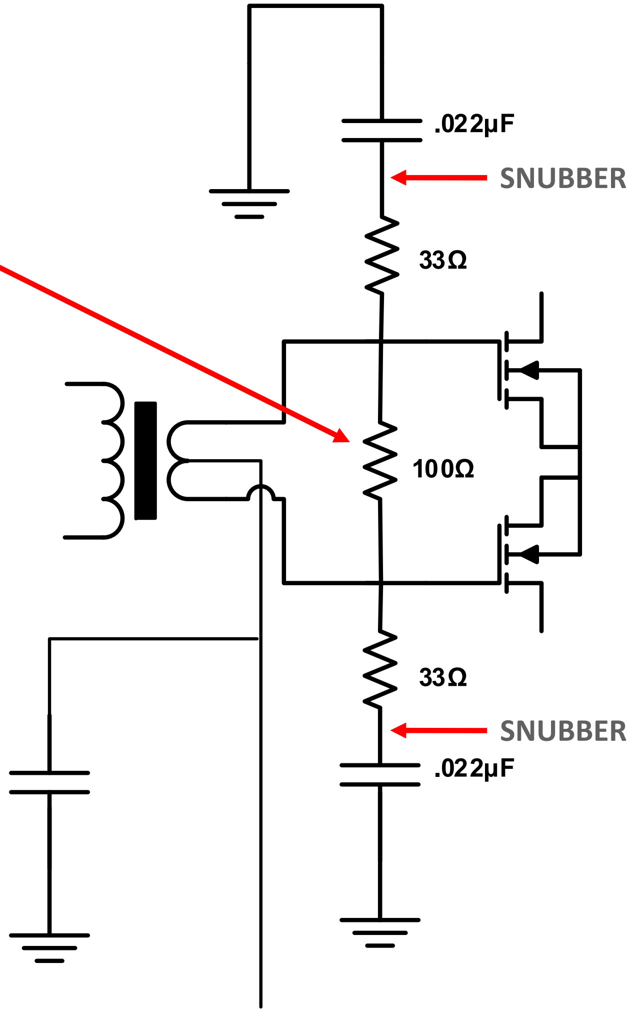




First Prototype Construction and Initial Testing

- "Snubber" networks needed between gates and ground to reduce gain at lower frequencies
- Added 100Ω swamping resistor between gates





- Oscillation and resulting spurs are gone
- Input return loss now 17-19dB depending on rf drive level

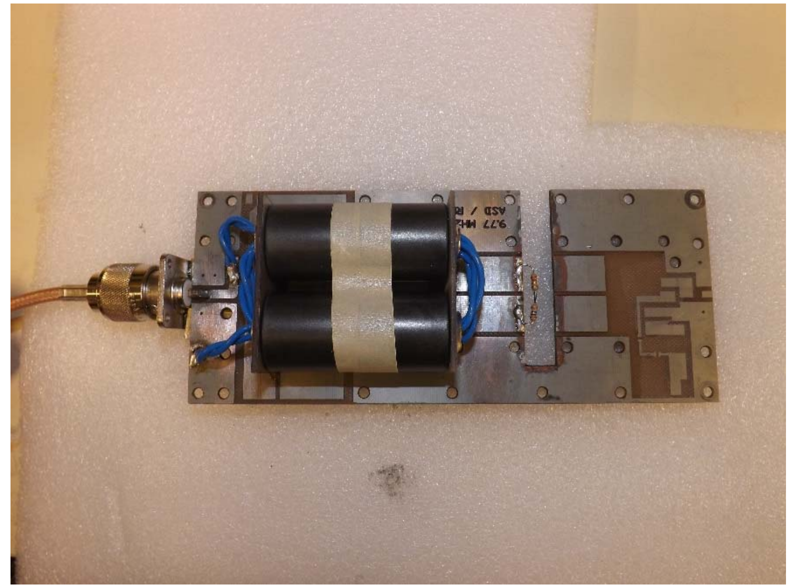
Output Transformer
-- Ferrites and Compensation

- Impedance measurements made using a spare board with a 12.5Ω resistance across primary winding

- Parallel capacitor across primary winding to optimize impedance seen by transistor:

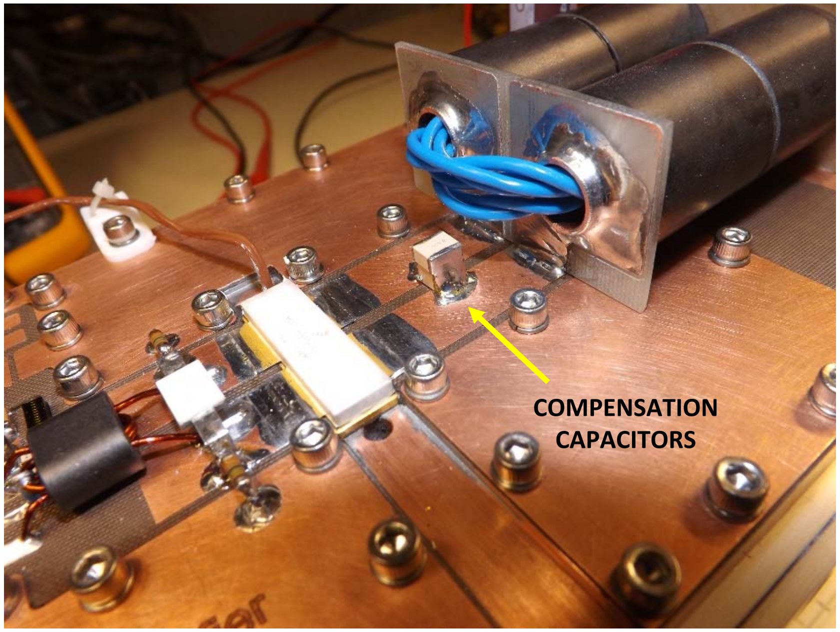
PARALLEL CAPACITOR	SECONDARY IMPEDANCE
NONE	112 + j27
1,000pF	74 – j29
1,470pF	62 – j30
1,690pF	53.2 – j31

- Little difference seen between #31 and #43 ferrites



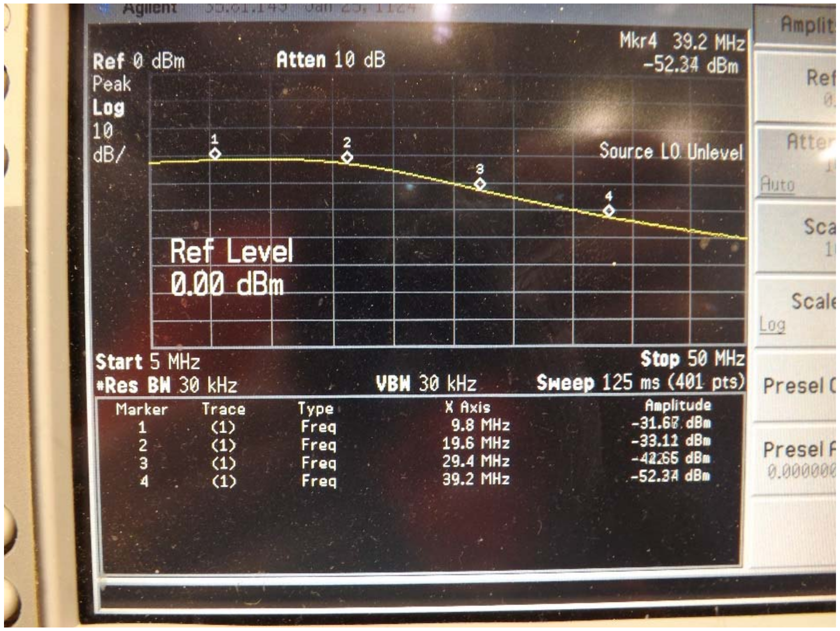
Optimization of Output Transformer Compensation

- Output transformer cores switched to #43 material
- Full-power efficiency measured for different compensation capacitor values
- Drain voltage = 50V



COMPENSATION CAPACITOR	RF INPUT POWER	RF OUTPUT POWER	GAIN	DRAIN CURRENT	EFFICIENCY
820 pF	1.84 watts	1,050 watts	27.56 dB	31.16 A	68.6%
1,000 pF	1.85 watts	1,130 watts	27.85 dB	31.09 A	73.9%
1,100 pF	1.98 watts	1,170 watts	27.71 dB	31.42 A	75.8%

Harmonics and Bandwidth

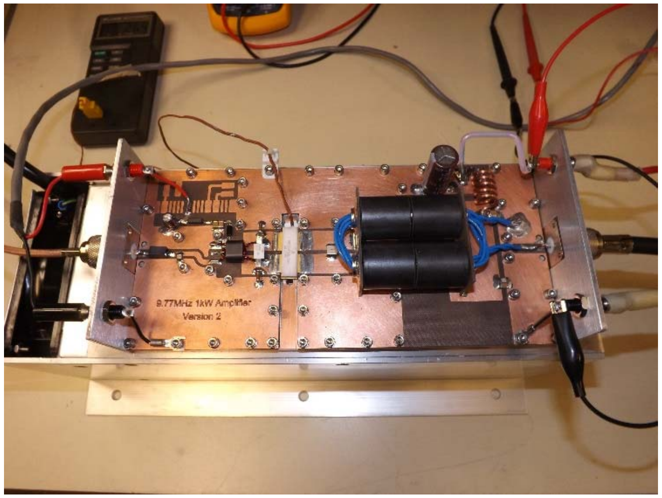


- Unfiltered harmonic amplitudes are quite high because of transformer coupling – *filtering required*

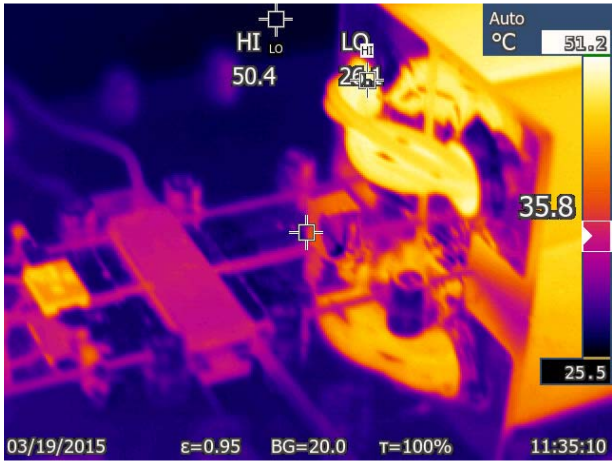
- Broad bandwidth – reasonable performance out to ≈ 15MHz

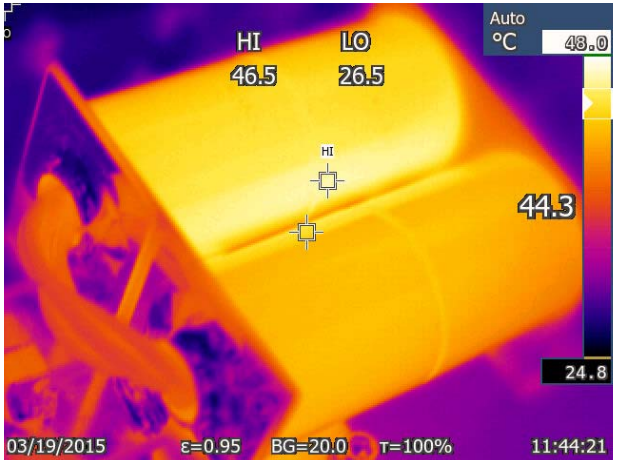
30-Volt Operation

- Thermal performance test:
  → *30 minutes continuous operation at saturation*
- Forced-air cooling of heatsink



RF INPUT POWER	RF OUTPUT POWER	GAIN	DRAIN CURRENT	EFFICIENCY	TRANSISTOR FLANGE TEMP
0.538 watts	422 watts	28.9 dB	18.42 A	75.56%	34.1° C

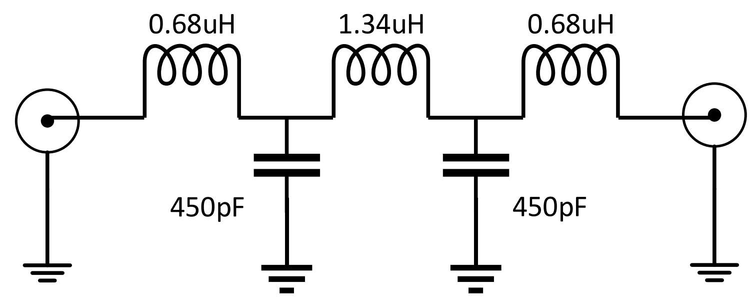




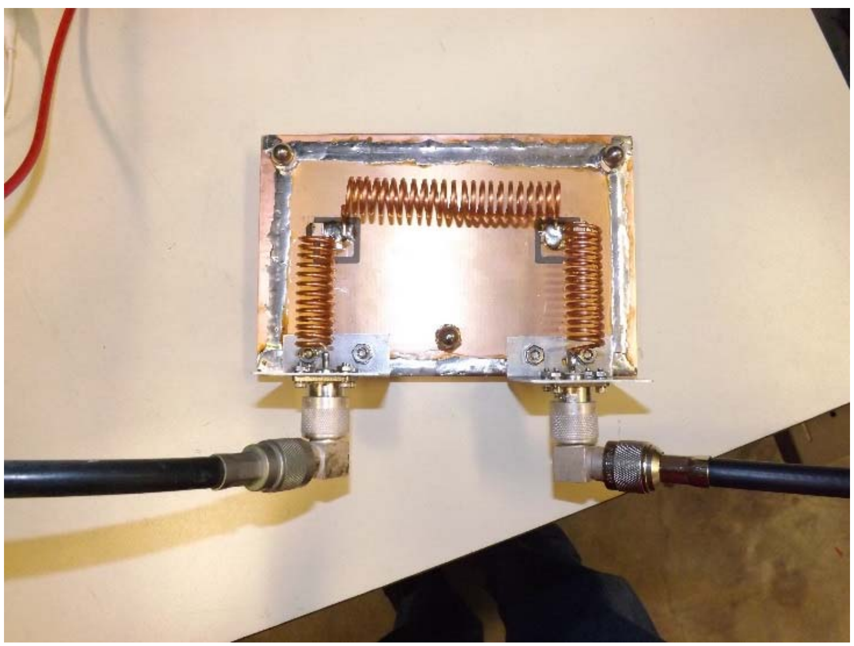
9.77MHz Output Harmonic Filter

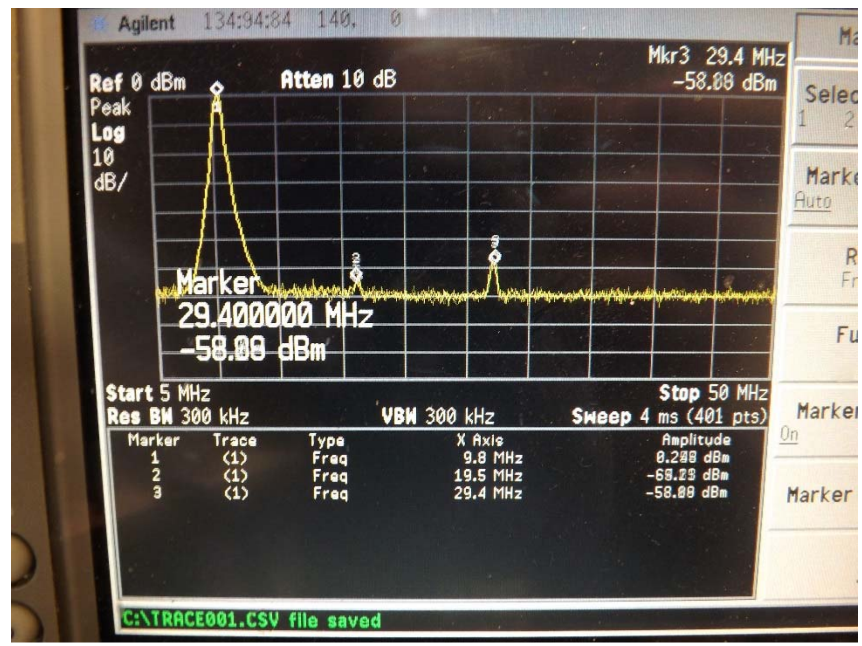
-- Five-Element 50Ω Low Pass Chebyshev

- 30-volt operation with harmonic filter increases efficiency:



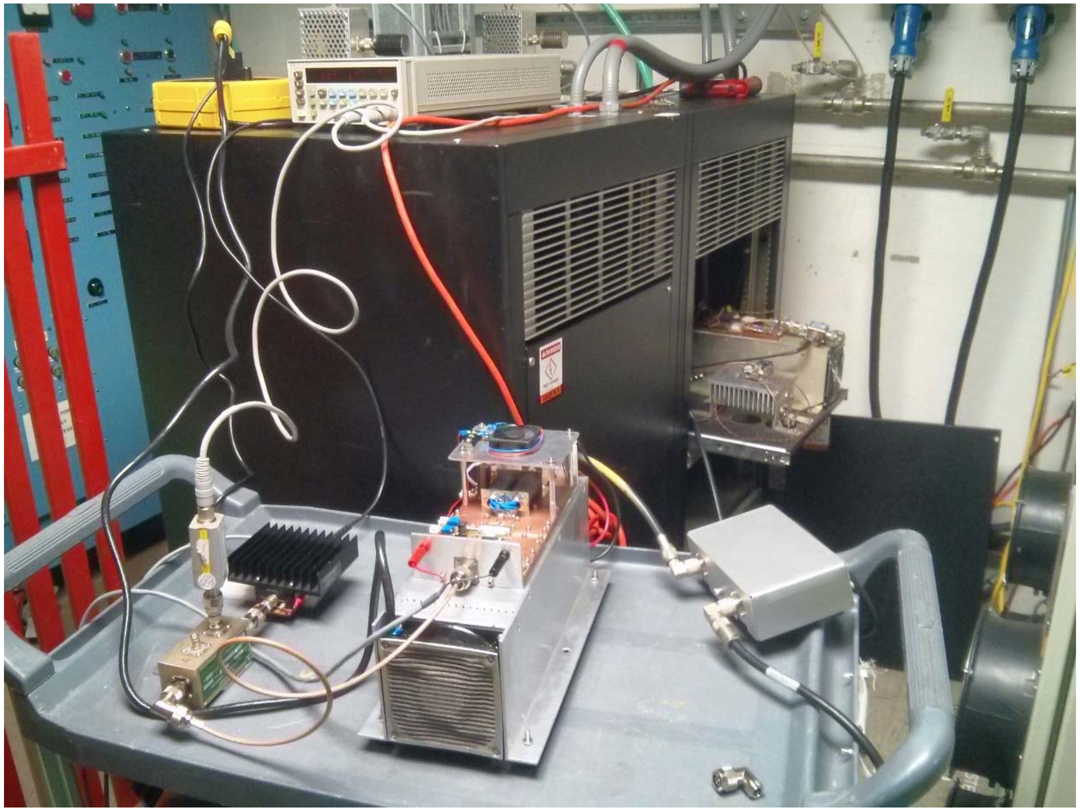
RF INPUT POWER	RF OUTPUT POWER	GAIN	DRAIN CURRENT	EFFICIENCY
1.28 watts	411 watts	25.06 dB	15.62 A	87.7%





System Test

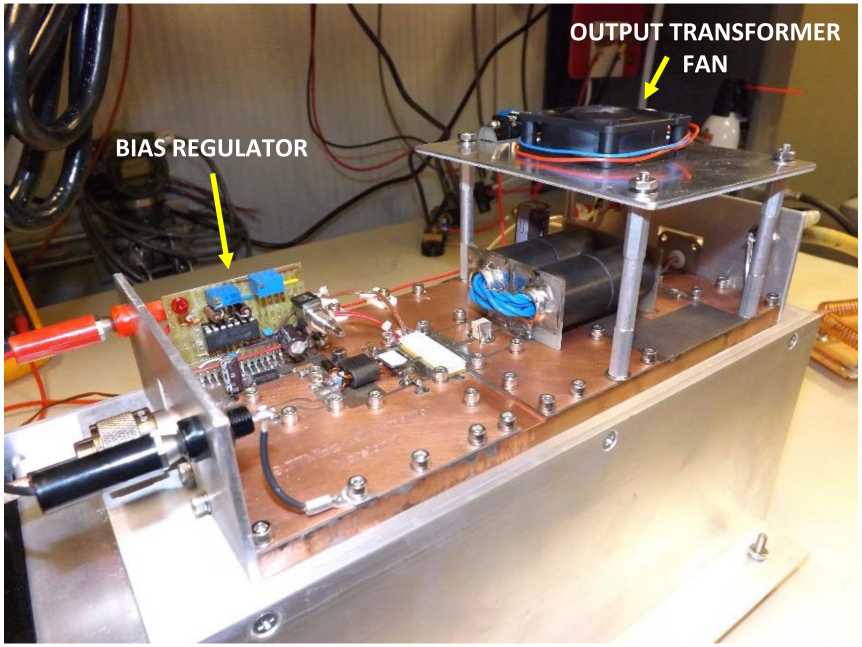
- First prototype tested in accumulator ring rf system under beam conditions:

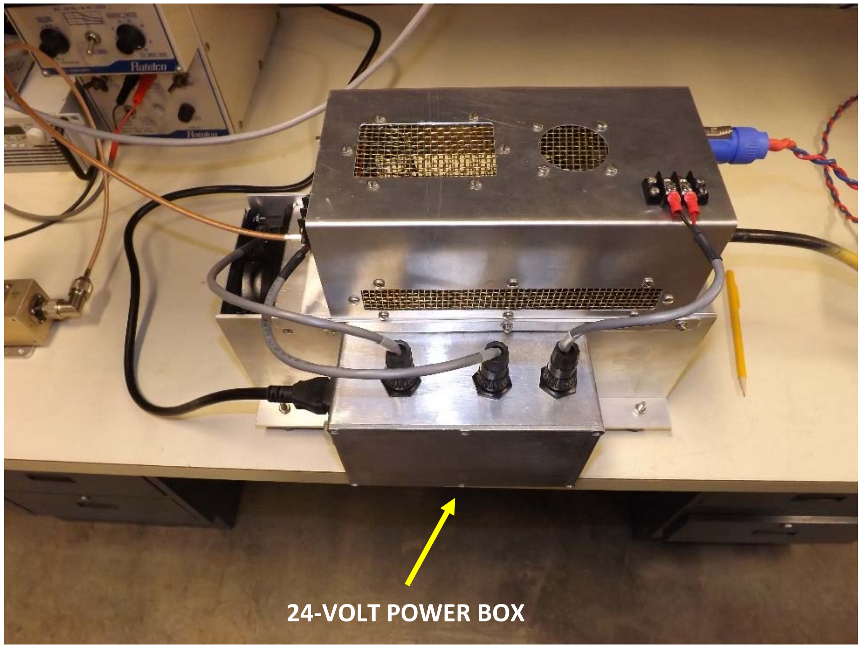


- No problems noted

Final Version – *Added Features*

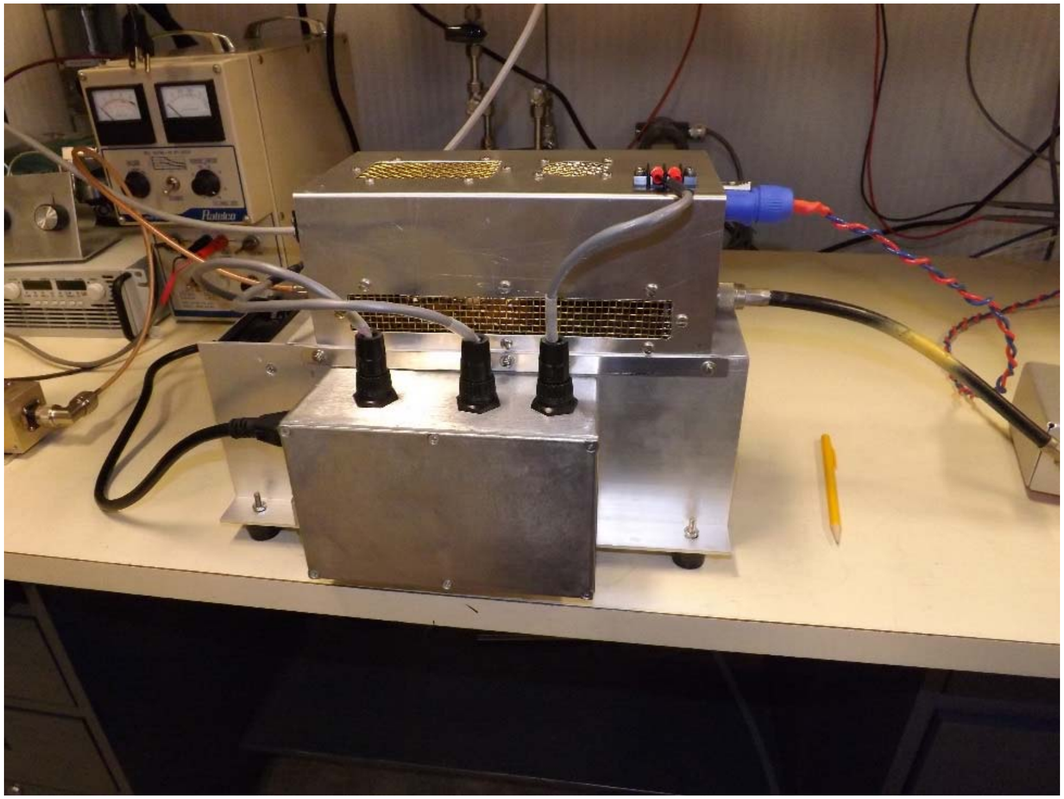
- Thermal tracking bias regulator
- Fan for output transformer
- Central 24-volt power for bias regulator and fans
- Shielded enclosure





9.77MHz Driver Amplifier -- *Summary*

- Four units will be built and tested
- Two units will be installed in rf systems in 2016-2017



352-MHz Solid State Amplifier Development

- **Ultimate goal**: Design and build a 352-MHz/200kW rf system that could be used for both the storage ring and booster

  → Achieve 2kW output per LDMOS device to minimize system complexity

  → Utilize a resonant cavity output combiner to reduce complexity and enhance efficiency

Initial R&D goal: Build a 12kW cw demonstration amplifier utilizing six 2kW amplifier modules driving a combining cavity:

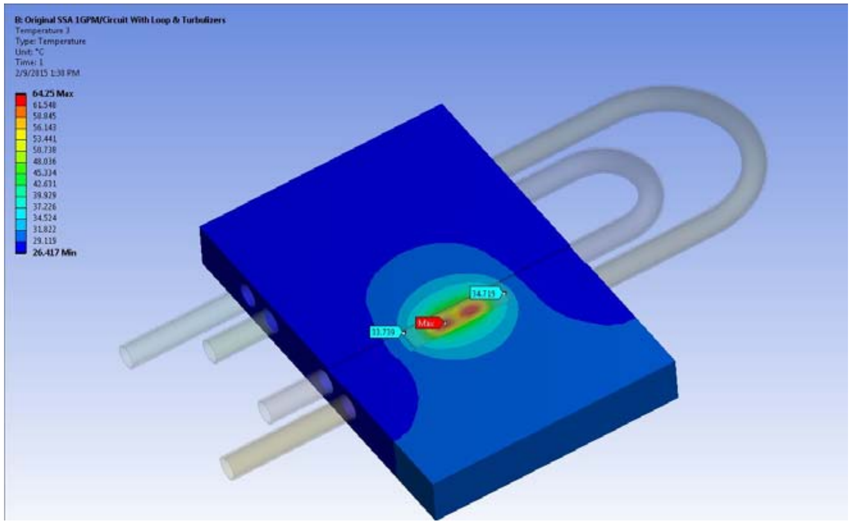
- 2kW cw output per module
- Module efficiency > 65%
- Single push-pull package
- Operate device at 60V
- Use Freescale (now NXP) MRFE6VP61KH25 device

352-MHz/2kW Amplifier Design --

Cooling System

- Conventional copper cold plate + carrier construction used for prototype amplifiers

- Thermal model developed and verified



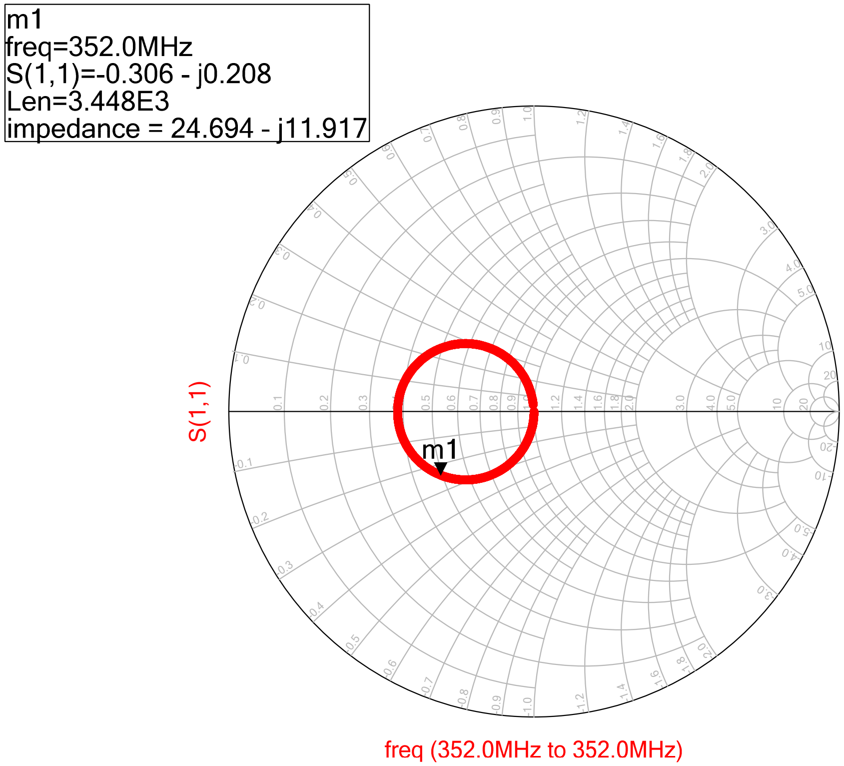
352-MHz/2kW Amplifier Design – A. Goel

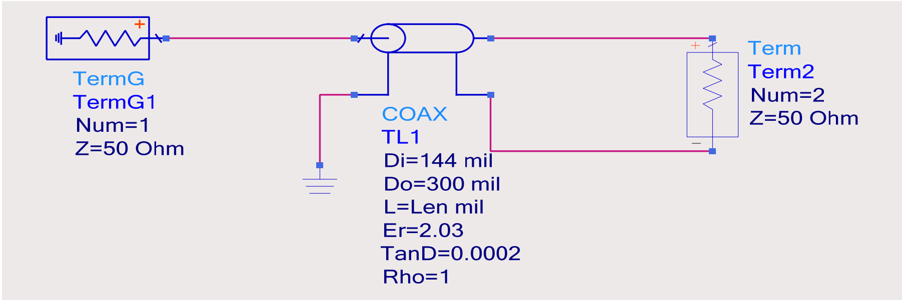
Source/Load Impedance from Simulation

- Source and load pull simulations provided the answer, but:
  - If starting impedance guesses are not correct, search space is the entire smith chart.
  - Large search space leads to model convergence errors
  - Iterative and time consuming
  - Prone to errors
- A better approach:
  - Use simultaneous Load and Source impedance optimization with specified goals of output power and efficiency.
  - Both ADS and MWO have simulation components that can do this

352-MHz/2kW Amplifier Design – A. Goel

Matching Network: Balun

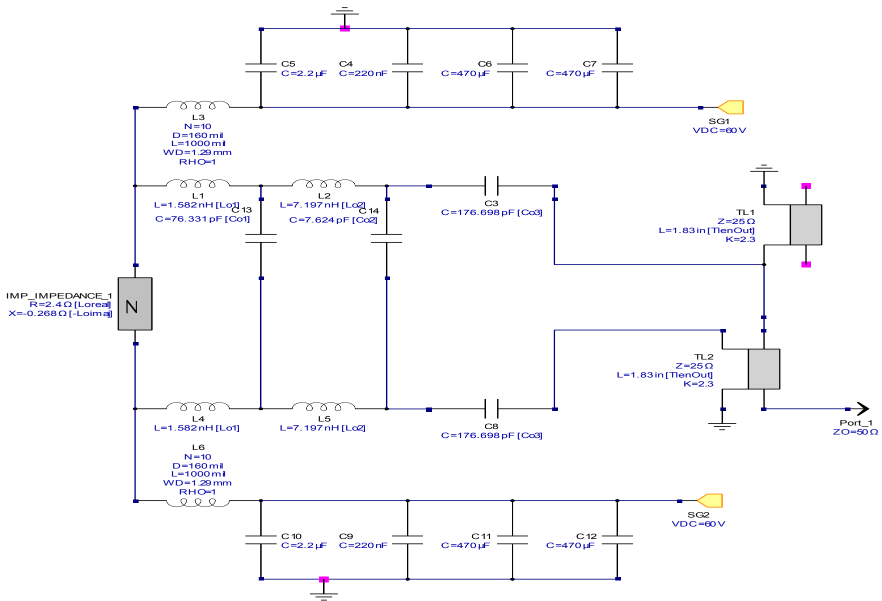


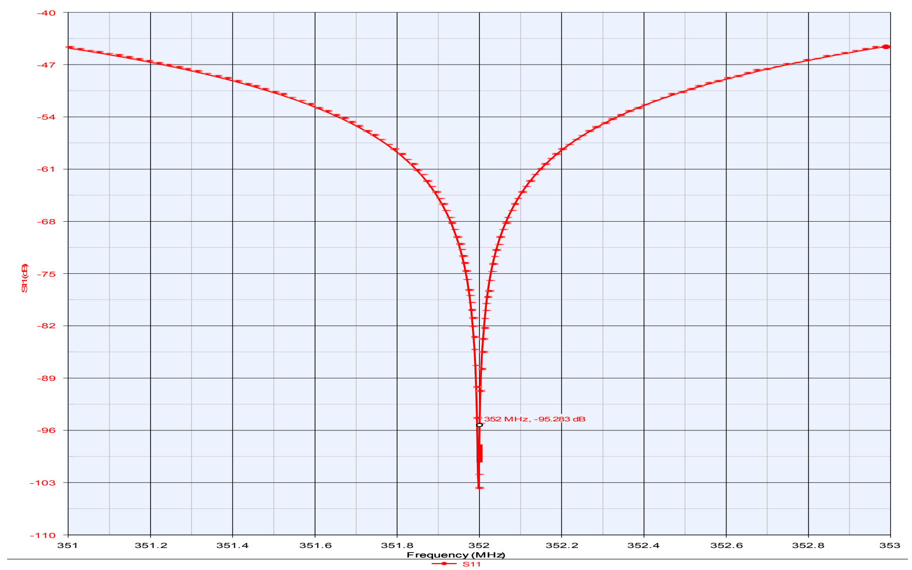


- Start with the balun and decide upon a practical length if using a coax balun
- 25 ohm coax used as balun on input and output:
  - Provides a complex 1:2 transformation ratio for real part in unbalanced mode
  - Practical length considerations prevented use of quarter wavelength

352-MHz/2kW Amplifier Design – A. Goel

Matching Network Design



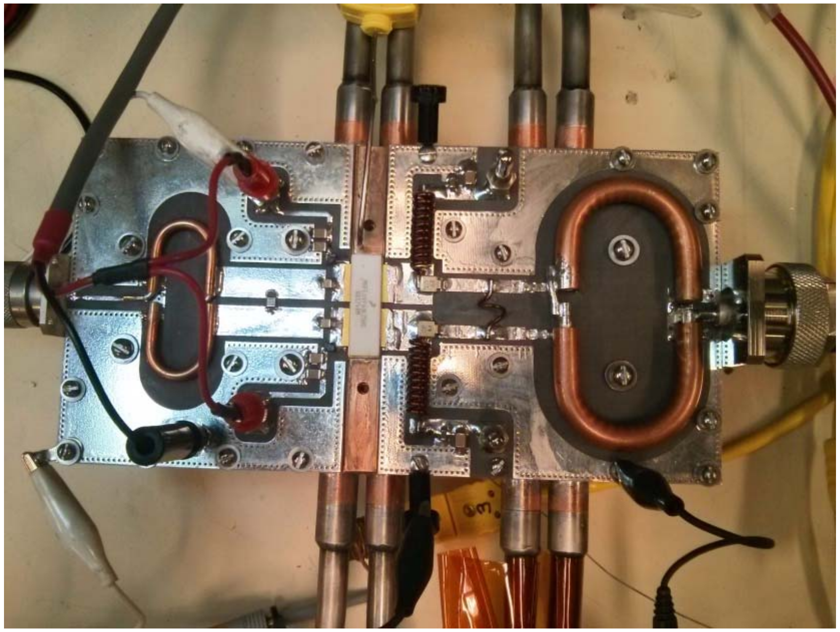


- Start with a lumped element LC matching network
- Take the conjugate of the complex impedance value obtained from the impedance optimization
- Convert results from an unbalanced simulation to balanced mode
- Bias filtering network included when designing the matching network
- Design the LC match such that inductors are confined to the series section and there is at least one series capacitor (for DC blocking)
- Replace the inductors with equivalent transmission lines
- Use the widest possible trace width for the input and output as this maximizes current carrying capability and makes soldering much easier

352-MHz/2kW Amplifier Design – A. Goel

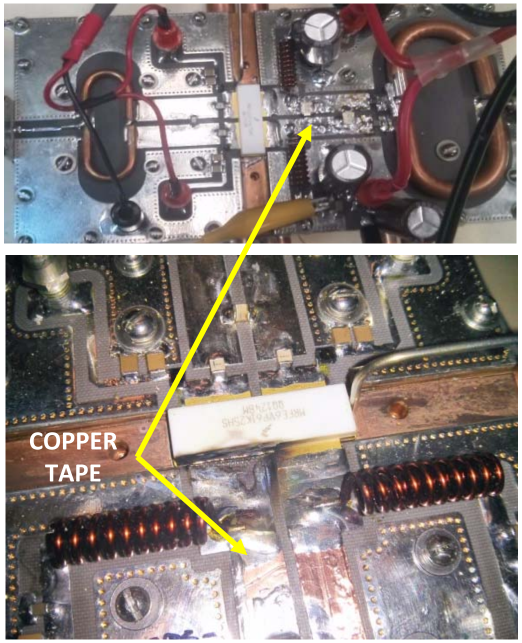
Version 1

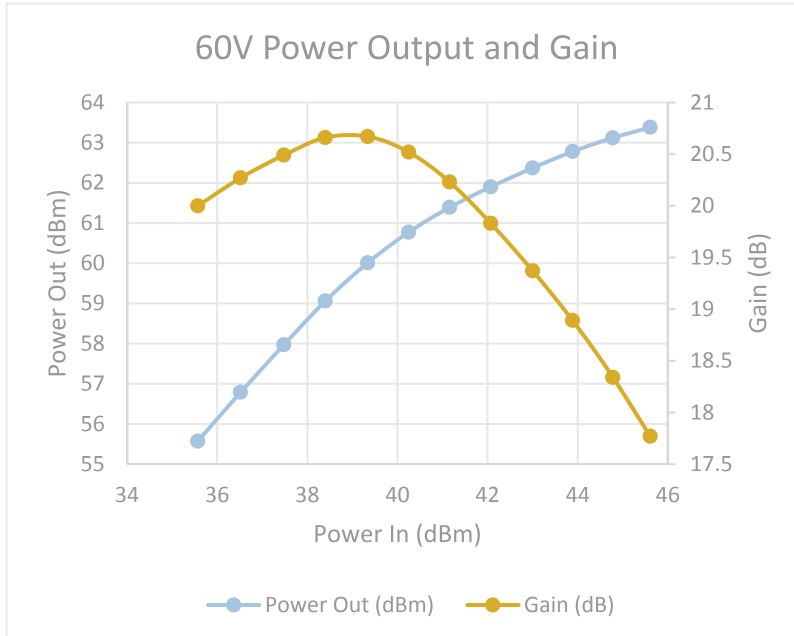
- Test at 60 volts
- Design based entirely on simulation results
- Input section match worked very well: *needed to move only 1 capacitor a few cm*
- Input return loss was -16dB.
- DC simulation results matched well
- ***Did not produce any power amplification -- output match problems!***
- Model errors are the most likely cause:
  - Model only validated at 50V operation
  - Model de-embedding at high power is difficult and error prone
  - Parameters used to develop high power models are taken under pulsed conditions
- Version 1 used to measure device DC dissipation and validate thermal models

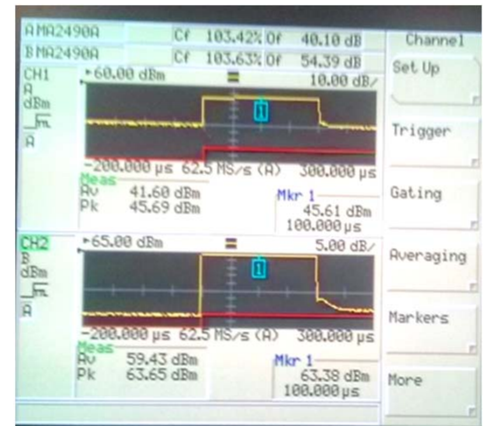


352-MHz/2kW Amplifier Performance – A. Goel

Modified Version 1



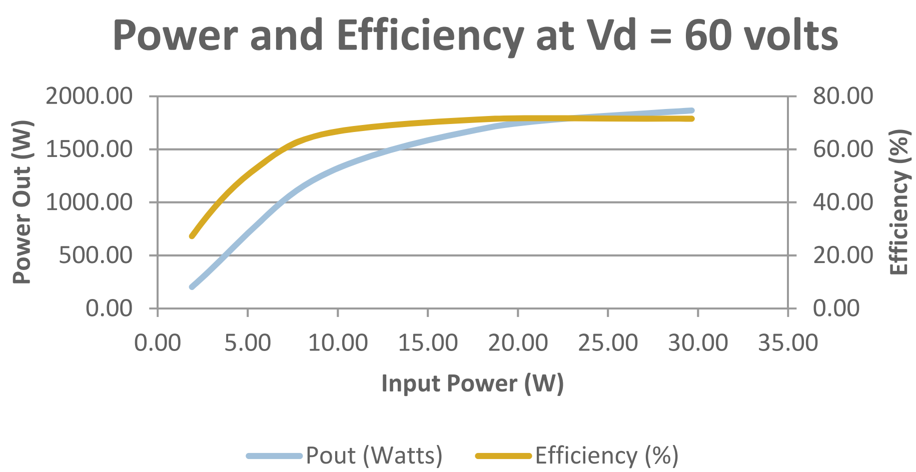




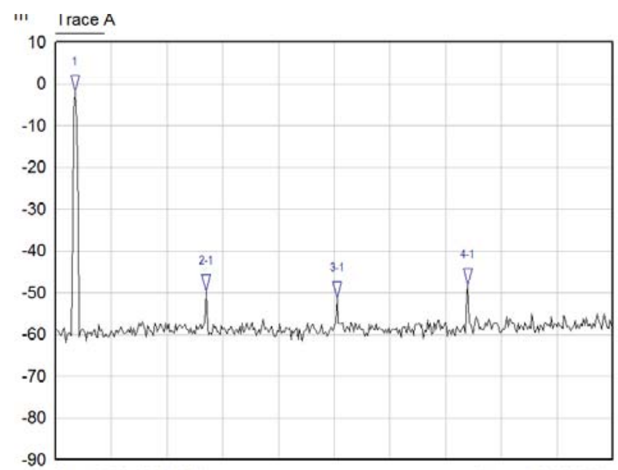
- Since input match was good no changes were made to input
- <u>Modified drain circuit traces with copper tape to increase width</u>
- Restricted components to all-metal mica caps to ensure thermal reliability
- After several days of tuning, stable pulsed operation achieved: 2.18kW, 10% duty cycle, 500Hz rep rate, Vd = 60 volts
- Used a mix of trend analysis and simulation to optimize component values
- *Destroyed one transistor in the process!*

352-MHz/2kW Amplifier Performance – A. Goel

Version 2

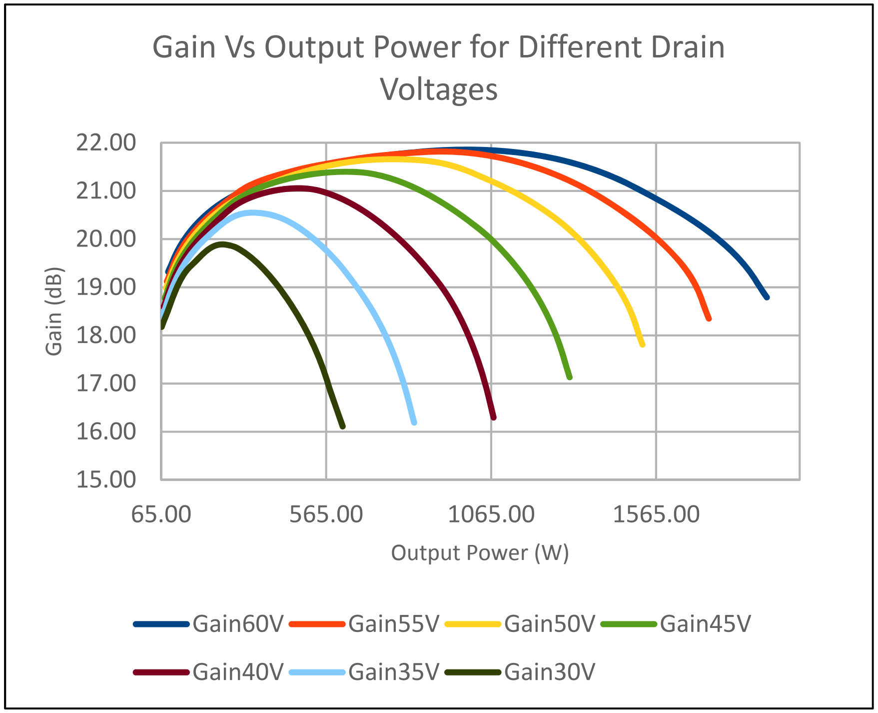


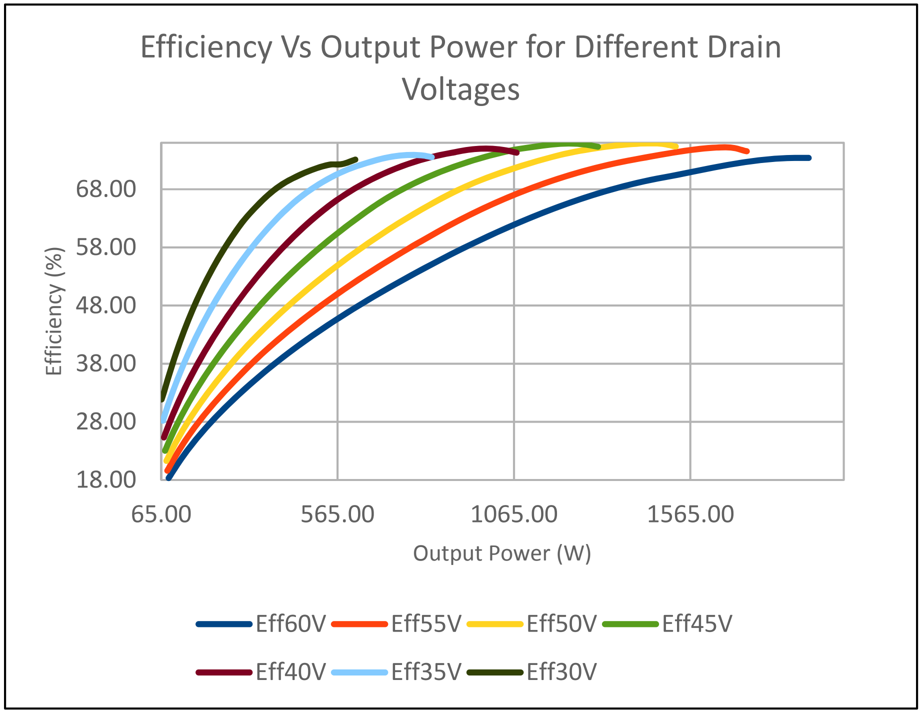
- Applied lessons learned from Version 1: Design new board with wider drain traces, and single break in trace for DC blocking
- No changes were made to input side
- After tuning: 1.86kW cw with 71.6% efficiency, 18dB gain
- Very stable and continuous operation for 2Hrs with no signs of thermal runaway or drift
- Harmonics are well controlled: at least -47dBC
- Further tune up has yielded 1-2% additional efficiency -- but no additional rf power



352-MHz/2kW Amplifier Performance – A. Goel

Version 2 – Drain Voltage Control

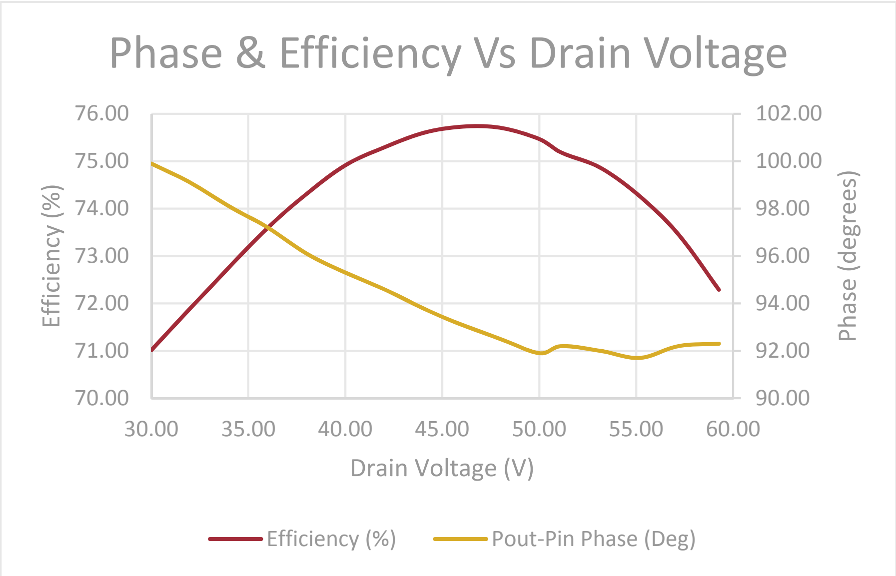


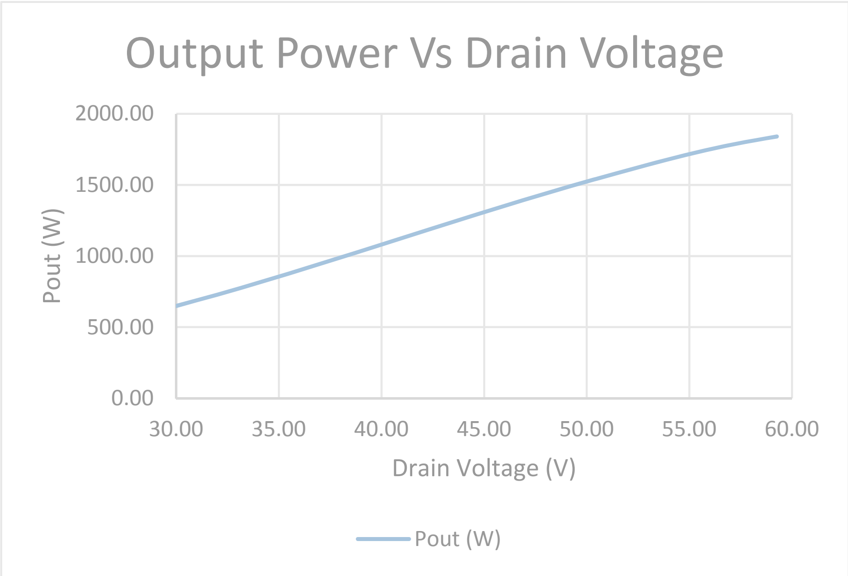


- The amplifier was operated at different drain voltages to characterize performance
- At least 70% efficiency is achievable over a wide output range by varying drain voltage

352-MHz/2kW Amplifier Performance – A. Goel

Version 2 – Drain Voltage Control

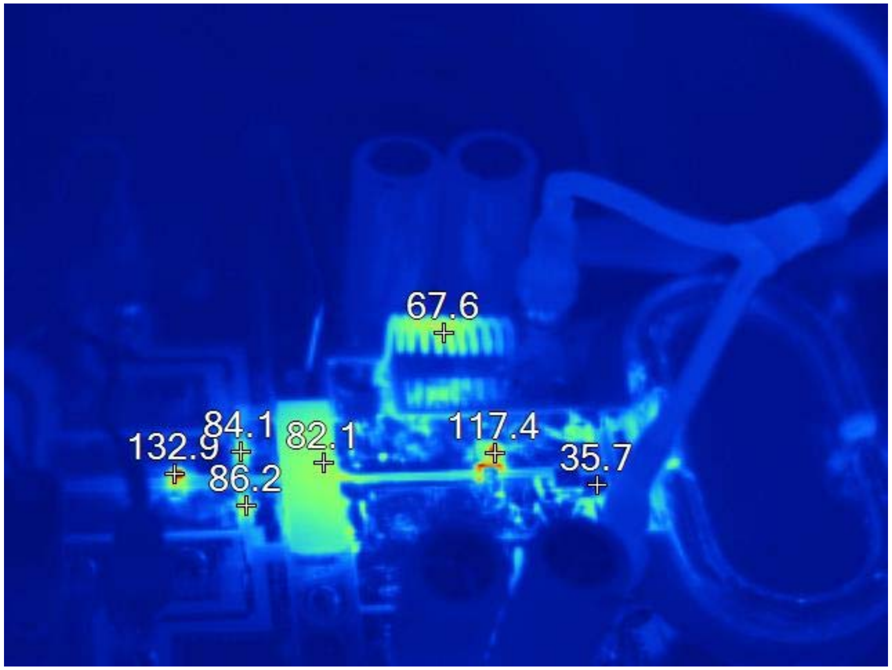




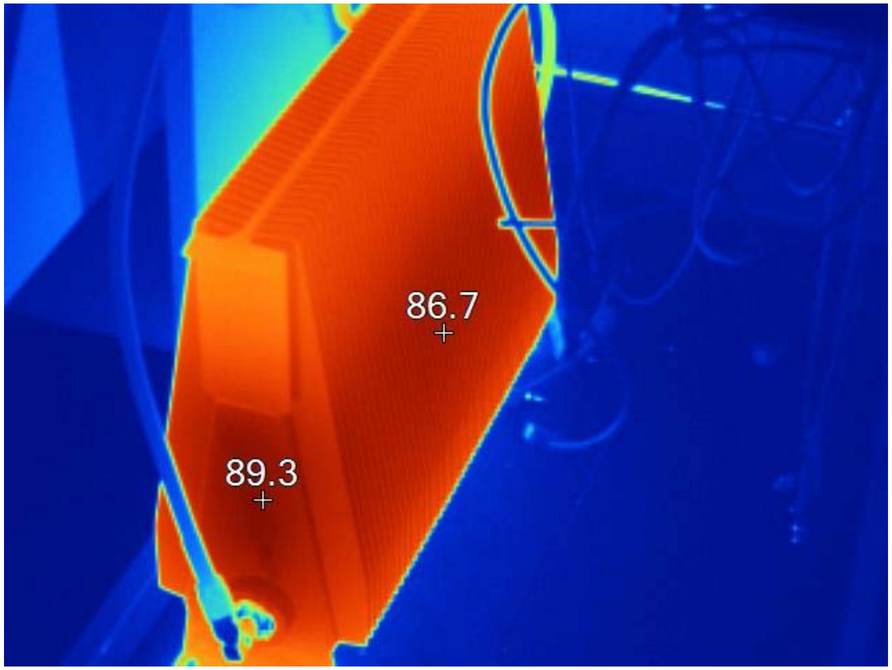
- Only 7.6 degrees of phase change from 30V to 60V change in drain voltage
- 1.27% Change in Efficiency for the same range
- Change in output power is very linear

352-MHz/2kW Amplifier Performance – A. Goel

Version 2 – Thermal



INFRARED SCAN OF BOARD AFTER FIFTEEN MINUTES OF OPERATION AT ≈ 1.7Kw



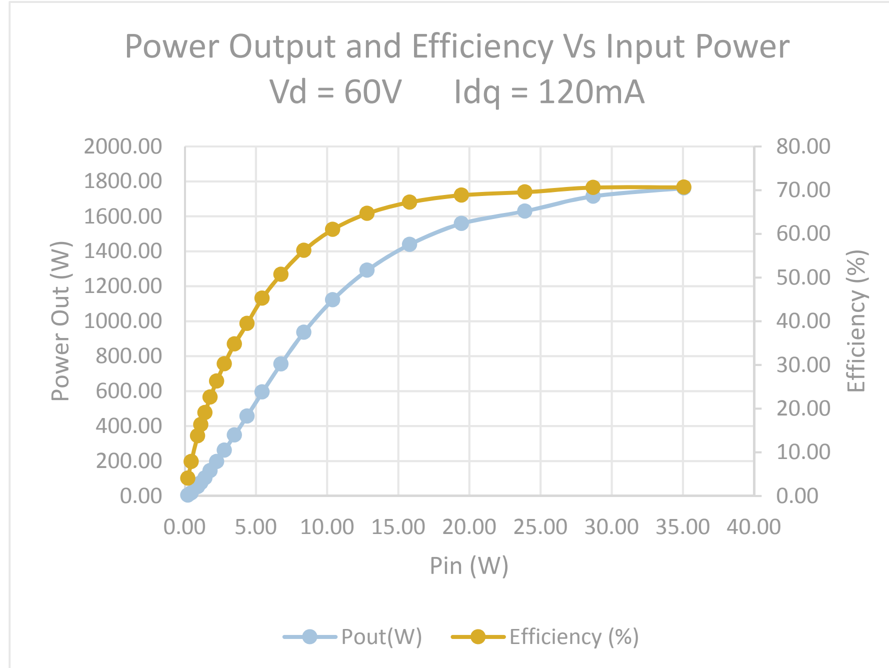
INFRARED SCAN OF 2kW RF LOAD

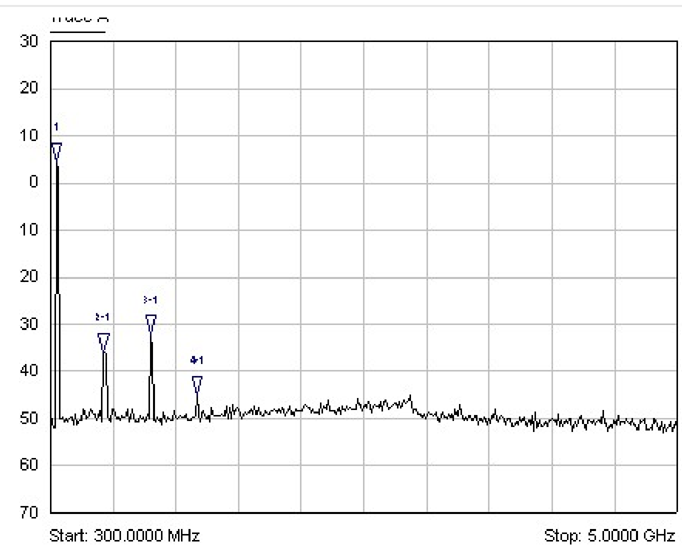
- Electro-thermal equilibrium reached after ten minutes of operation
- Transistor flange temperature reached 98^{o}C, below the manufacturer recommended maximum of 150^{o}C
- Passive components need better cooling

352-MHz/2kW Amplifier Performance – A. Goel

Version 2 – Replication

- Identical electrical design was replicated with slight modifications to the cold plate and carrier
- 1.76kW produced at first turn on -- *no tuning needed*
- All performance parameters closely matched the first prototype
- Hand made components (balun and bias filter inductors) may be the cause of performance variations



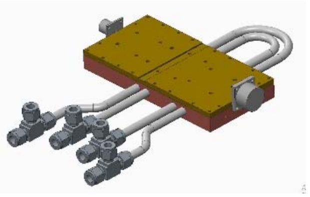


Thermal Challenges

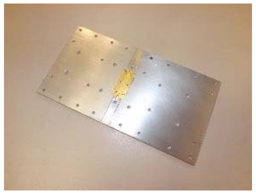
- Operation at 60 volts and 2kW rf power will require enhanced cooling to prevent premature failure of transistor and passive components

- Several cooling strategies are being considered:

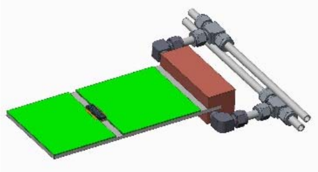
  → *Conventional copper cold plate + copper carrier:*



  → *Conventional copper cold plate + heat spreader:*



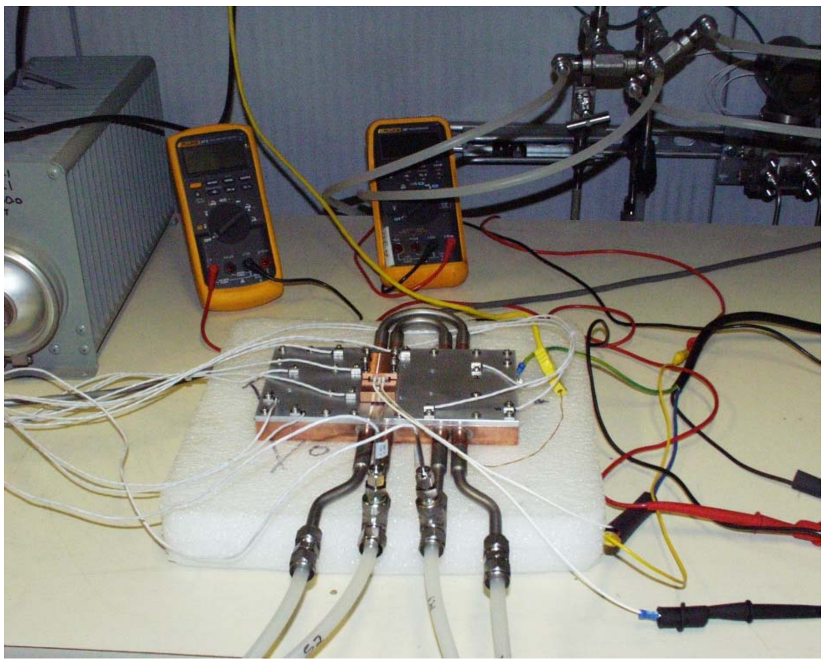
  → *Conventional copper cold plate + vapor chamber:*



- <u>*Tests are underway to determine the most practical solution*</u>

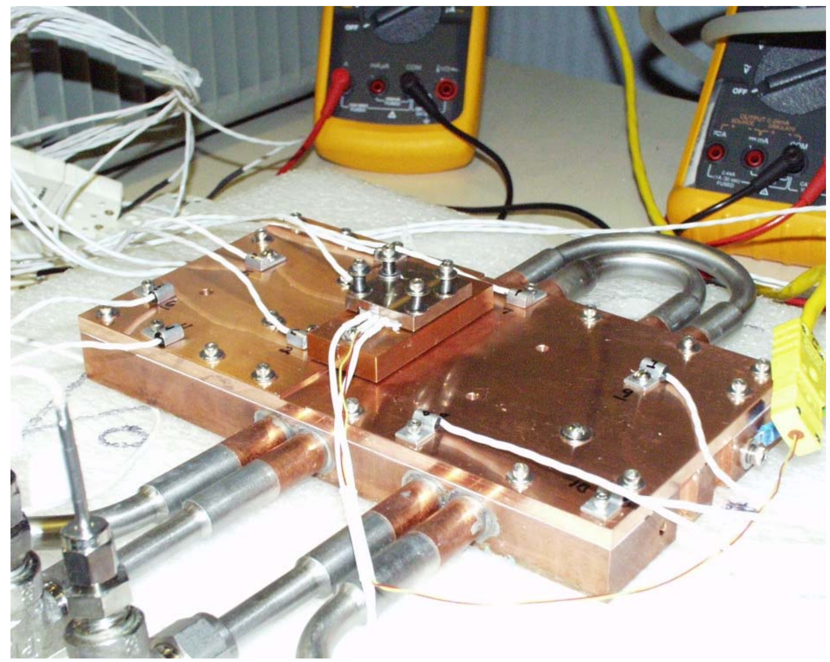
Thermal Tests -- *Copper Carrier and Euclid Heat Spreader on Water-Cooled Cold Plate* – *D. Bromberek*

500-WATT CERAMIC HEATER AND SPREADER BLOCK TO SIMULATE TRANSISTOR THERMAL FOOTPRINT



EUCLID ALUMINUM HEAT SPREADER

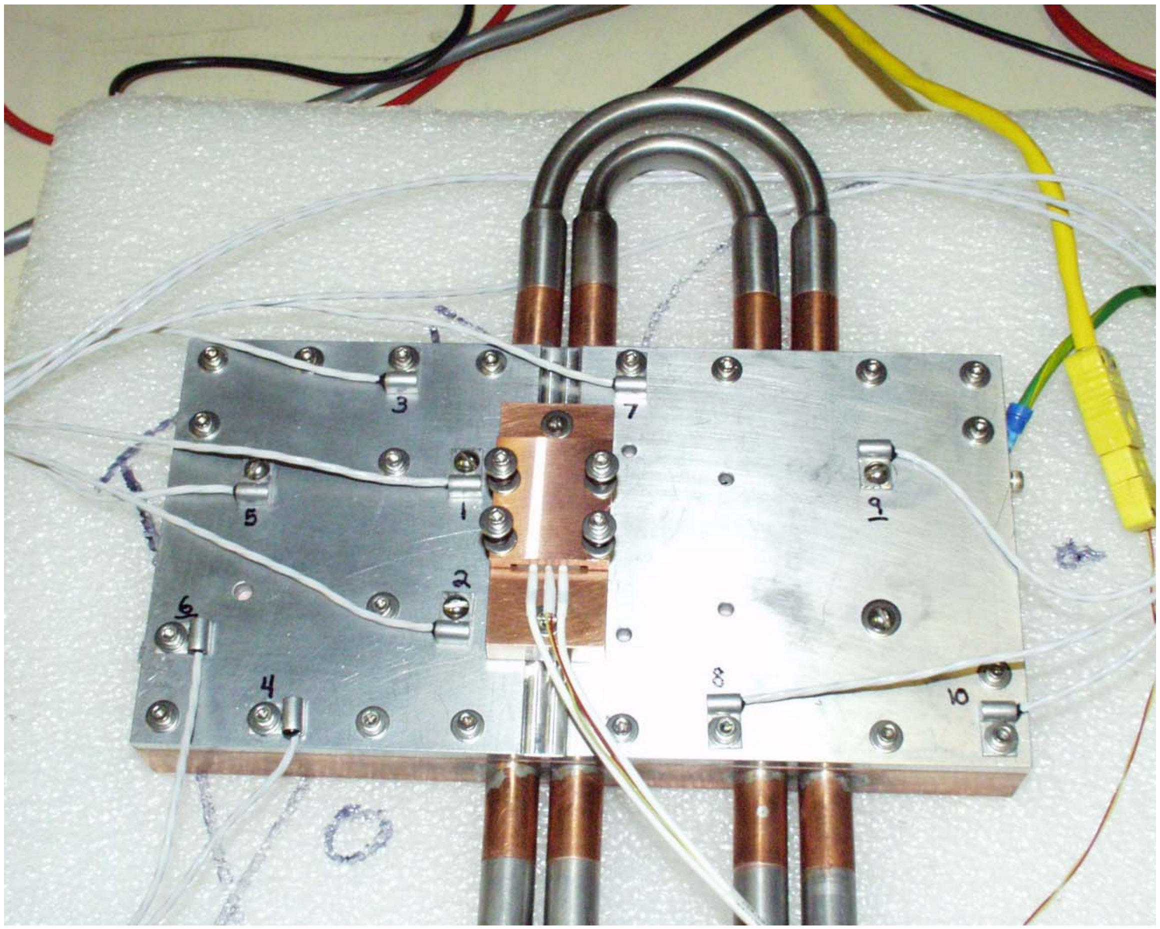
Euclid TechLabs LLC -- Dr. Chunguang Jing, Vice President for Engineering



COPPER CARRIER

Thermal Tests -- ***Copper Carrier and Euclid Heat Spreader on Water-Cooled Cold Plate –*** ***D. Bromberek***

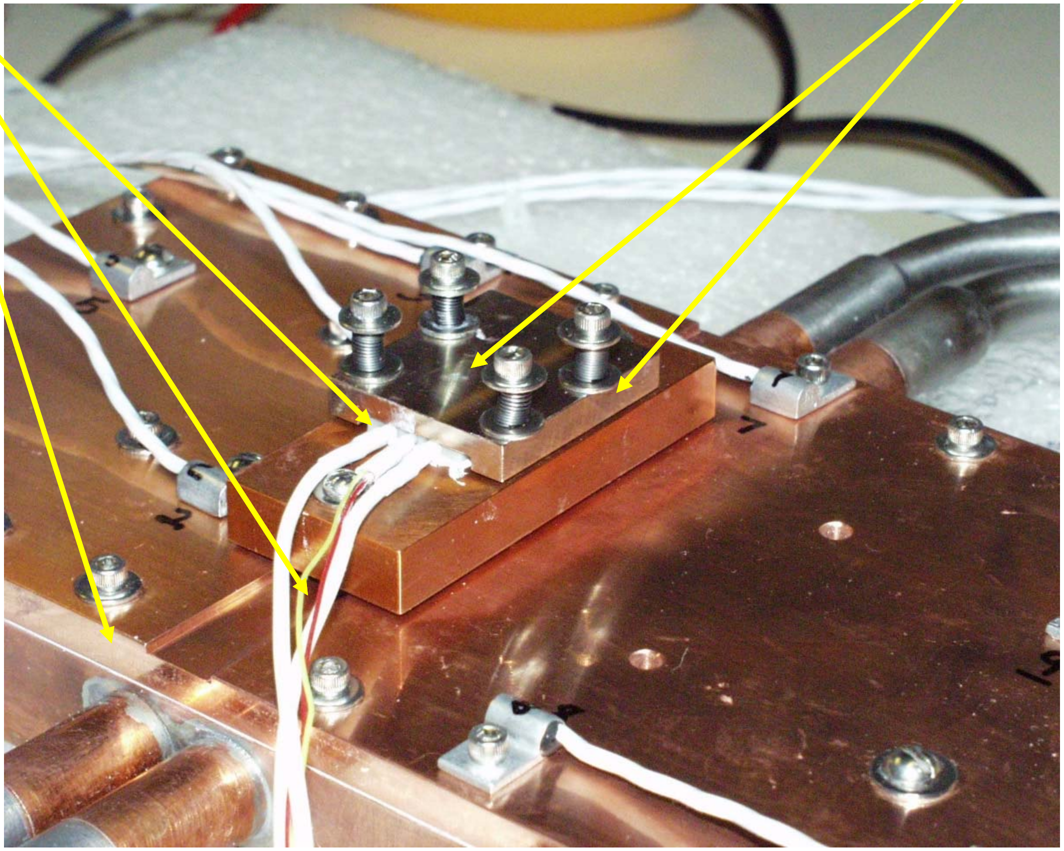
RTD MEASUREMENT LOCATIONS



Thermal Tests -- *Copper Carrier and Euclid Heat Spreader on Water-Cooled Cold Plate – D. Bromberek*

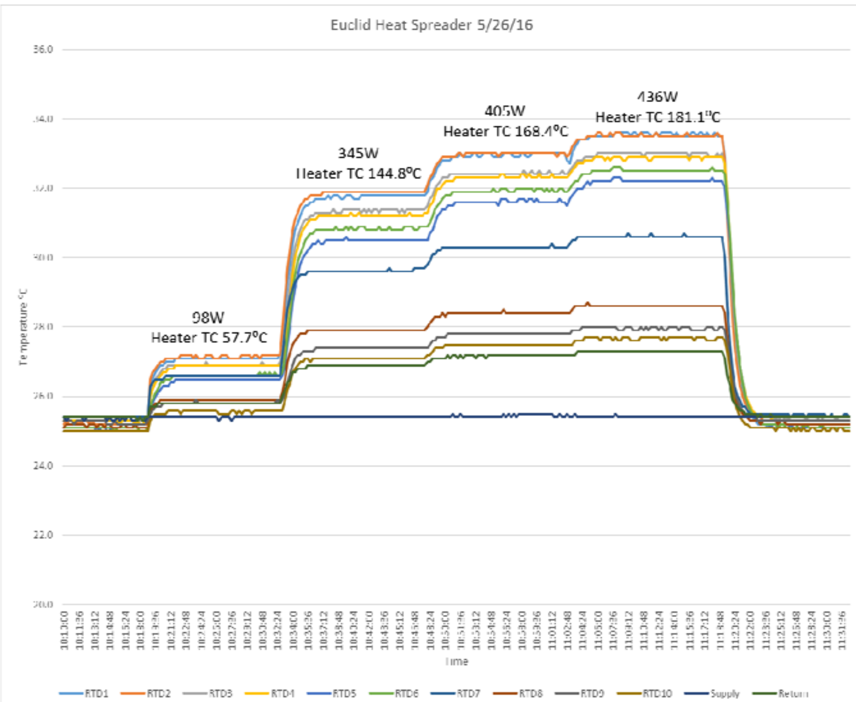
500-WATT HEATER WITH INTERNAL THERMOCOUPLE AND MOUNTING BLOCK

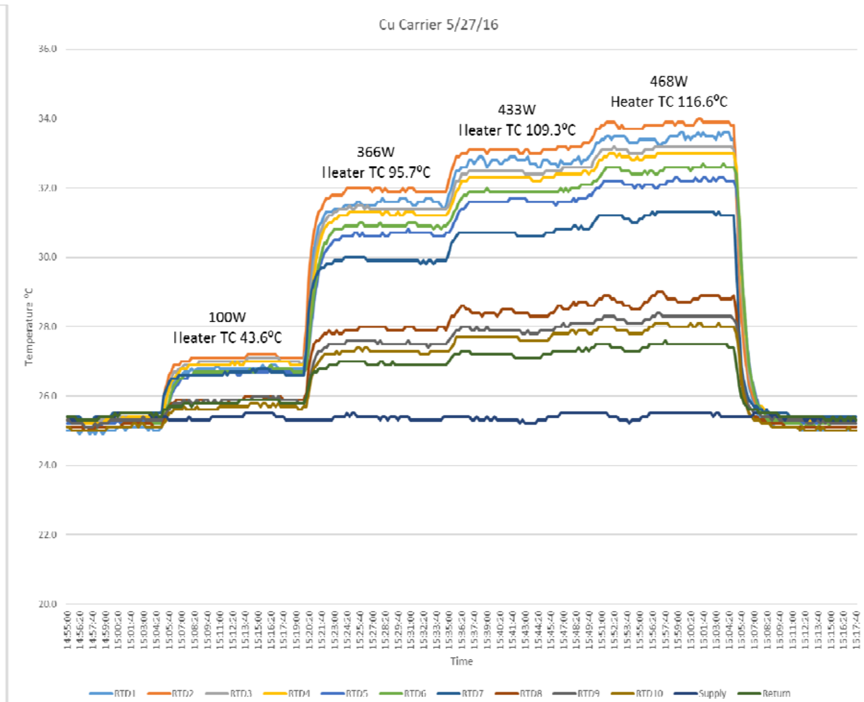
THERMAL GREASE JOINTS



Thermal Tests -- *Copper Carrier and Euclid Heat Spreader on Water-Cooled Cold Plate* – D. Bromberek

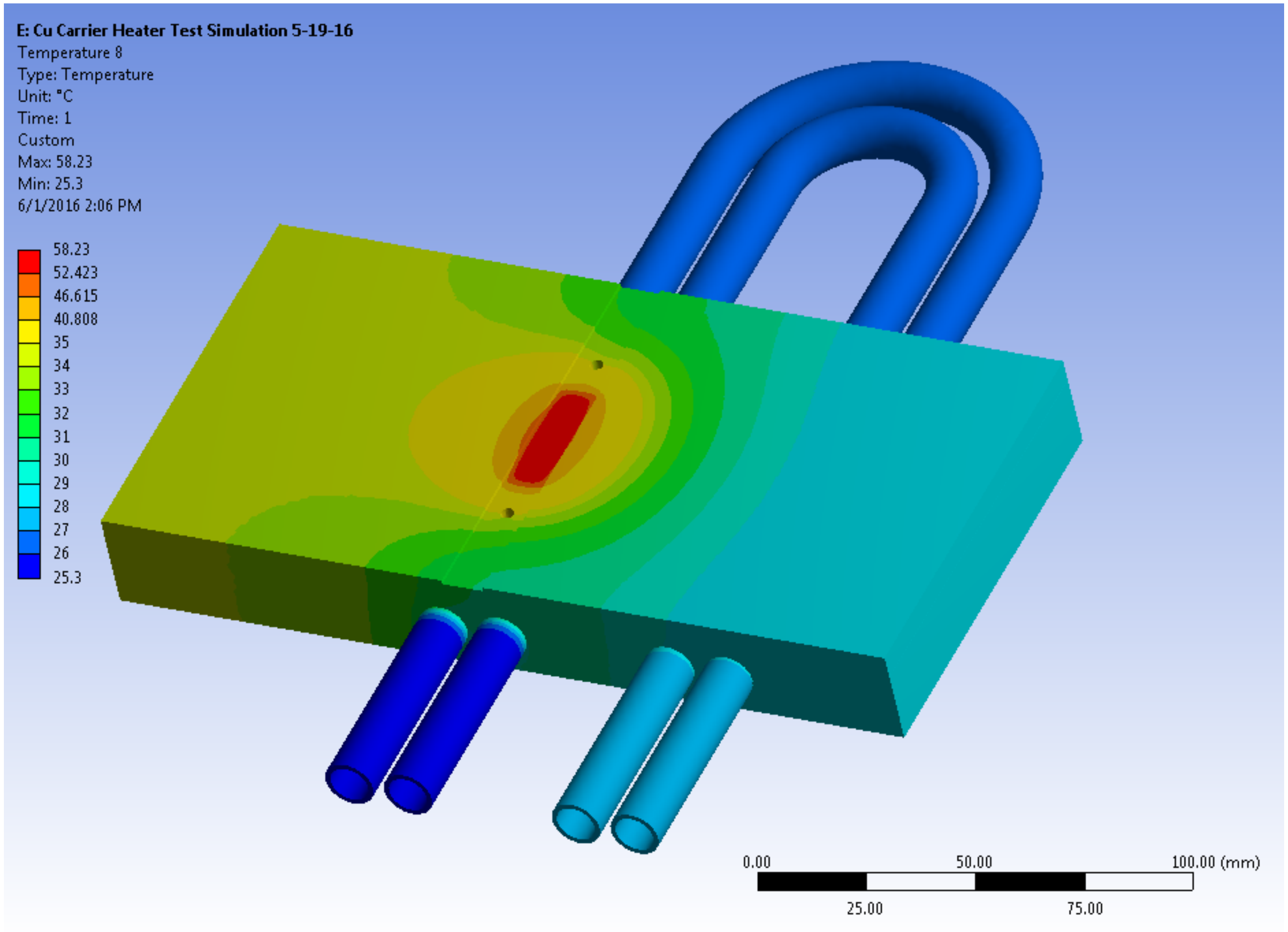
- Multiple tests run on both units …….. results very repeatable
- Heater voltage steps of 50, 100, 110, & 115VAC at 15-minute intervals
- Tests limited by thermal grease maximum temp (~200^{o}C) and heater rated voltage
- Copper carrier outperformed Euclid heat spreader due to placement of water channels directly under heat source rather than around perimeter





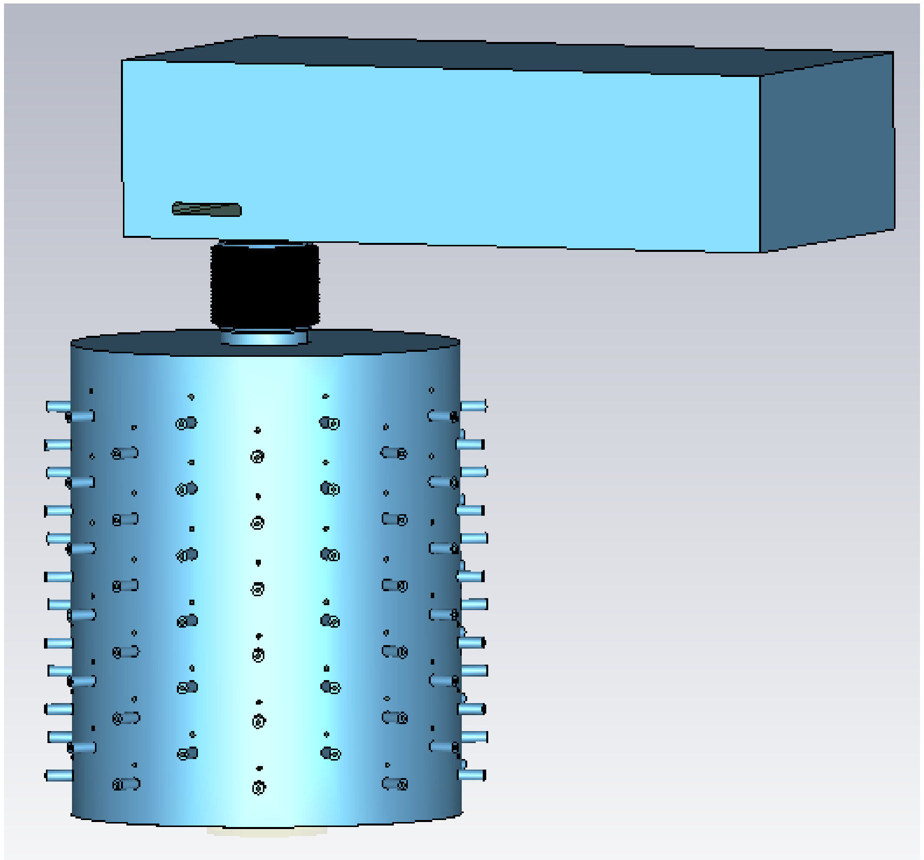
Thermal Tests -- *Copper Carrier and Euclid Heat Spreader on Water-Cooled Cold Plate – D. Bromberek*

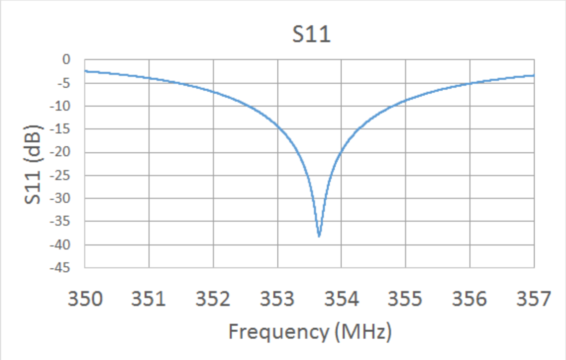
ANSYS SIMULATION RESULTS OF HEATER BLOCK TEST CONFIGURATION



Output Cavity Combiner Design -- G. Waldschmidt

- Design for 100 kW minimum
- 108 input ports for solid state amplifier modules – *1.5kW per amplifier nominal*
- Eighteen individual 6-port panels, utilizing rf spring contacts
- Heavily over-coupled output coupler to reduce cavity losses
- Peak fields minimized for high gradient operation
- Single WR2300 full height waveguide output feed

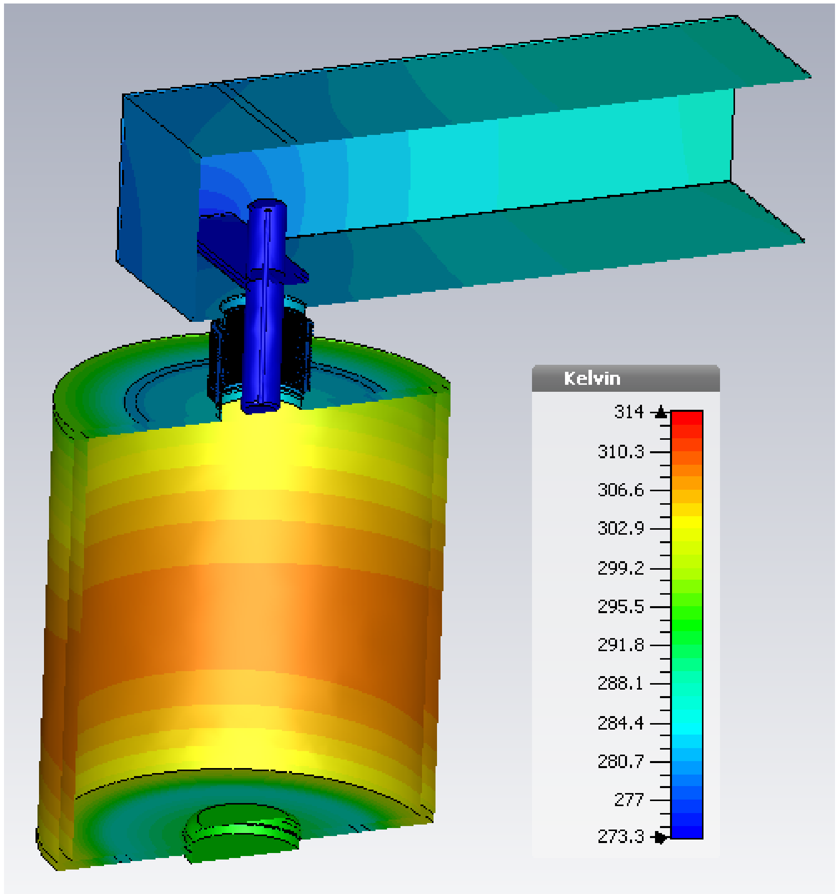




Output Cavity Combiner Design
-- Thermal and Electrical Simulations at 100kW -- G. Waldschmidt

- Peak fields (output coupler and tuner) are less than 0.5 MV/m
- T-bar geometry facilitates conductive and convective cooling
- Water cooling of output coupler with conductive cooling of waveguide is planned
- Top and bottom plate will be water cooled
- Tuner cooling is conductive through contact springs
- Remaining geometry is air cooled

THERMAL PROFILE WITH 100kW INPUT POWER

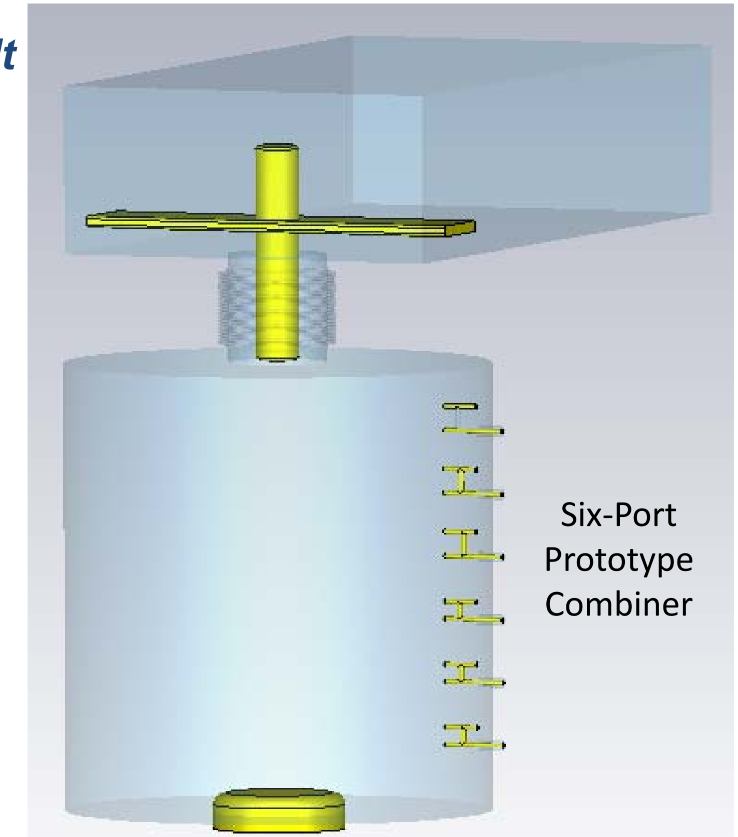


WATER COOLING: T-BAR OUTPUT COUPLER, TOP AND BOTTOM PLATE

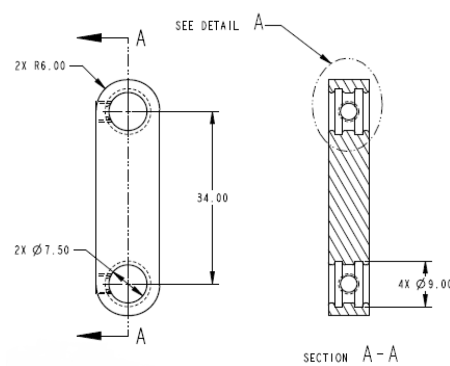
FORCED AIR COOLING: CAVITY AND BELLOWS

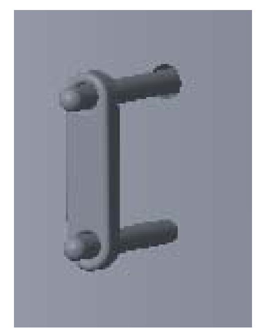
Output Cavity Combiner Design
-- 6-Port / 12kW Prototype – *G. Waldschmidt*

- 12kW prototype is based on full cavity combiner design, with one 6-port panel populated with input connectors and coupling loops
- Six 2kW amplifiers will be used
- Cavity built from aluminum with silver plating
- Output coupler bellows is adjustable to accommodate additional amplifiers
- Tuner has ± 3MHz tuning range
- Input couplers are tunable with a sliding cross member fitted with fingerstock rf contacts



Six-Port Prototype Combiner

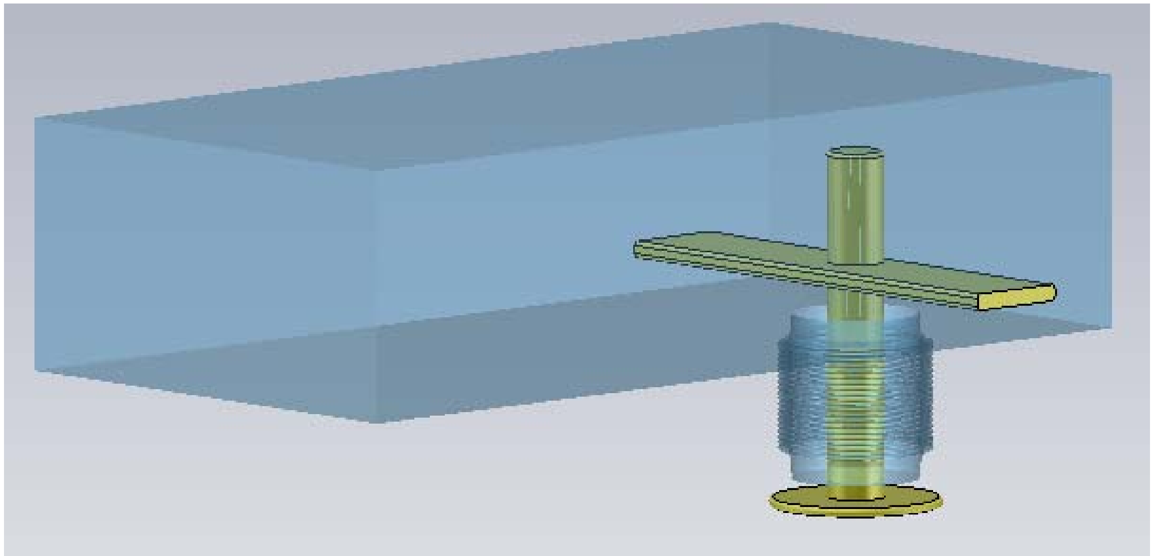


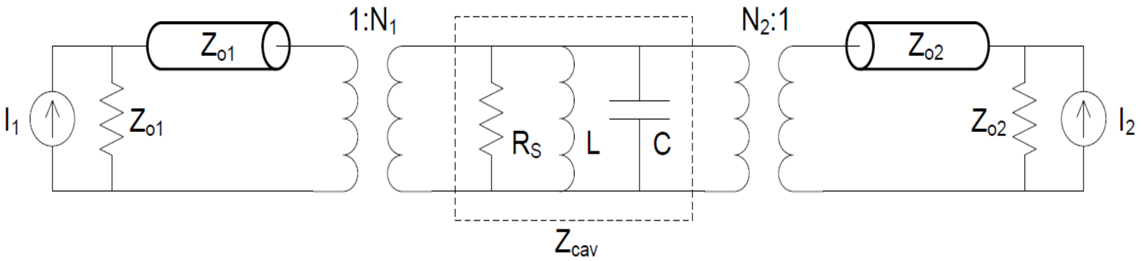


Adjustable input coupling

Output Cavity Combiner Design
-- Waveguide Transition Tuning – G. Waldschmidt

- T-bar waveguide transition designed as matching element for waveguide
- Permits internal cooling of output coupler and facilitates higher power handling
- Allows flexibility for number of amplifier feeds





Algorithm for sequential input coupler tuning of prototype cavity algorithm:

$$\Gamma_m := \frac{-(m-2)-N}{m+N}$$

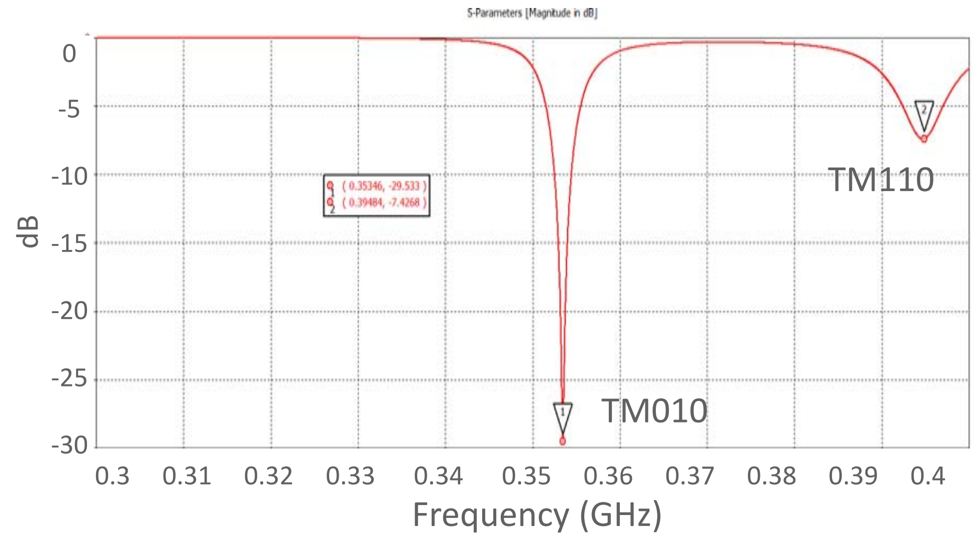
Critically matched response: $\Gamma := \frac{1-N}{N}$ $\beta := \frac{1}{2 \cdot N - 1}$

Output Cavity Combiner Design

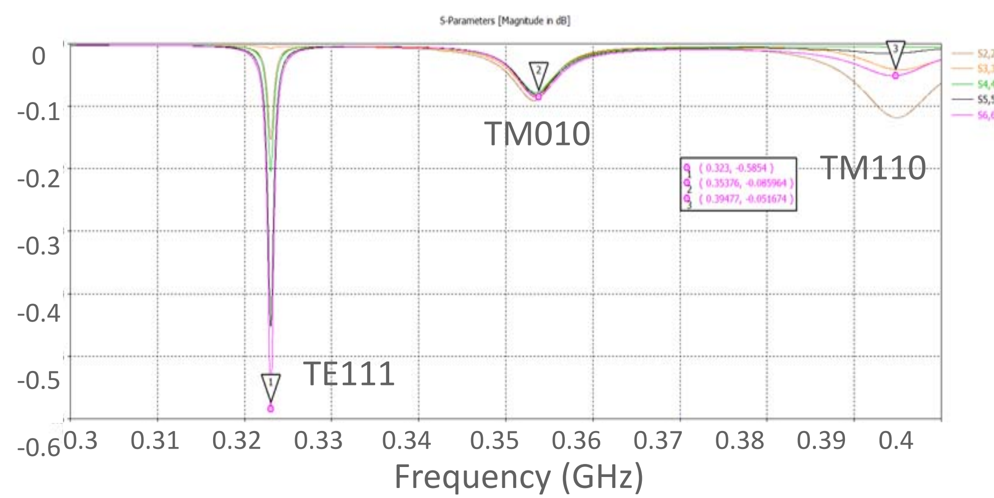
-- Other-Order Modes – ***G. Waldschmidt***

- Input couplers couple to other cavity modes that are within amplifier bandwidth
- Multiple input couplers may tend to cancel fields due to opposite circulation of magnetic flux
- Field non-uniformity is compensated at 352 MHz, but not at other modes so cancellation is not complete
- Bandpass filter is being considered

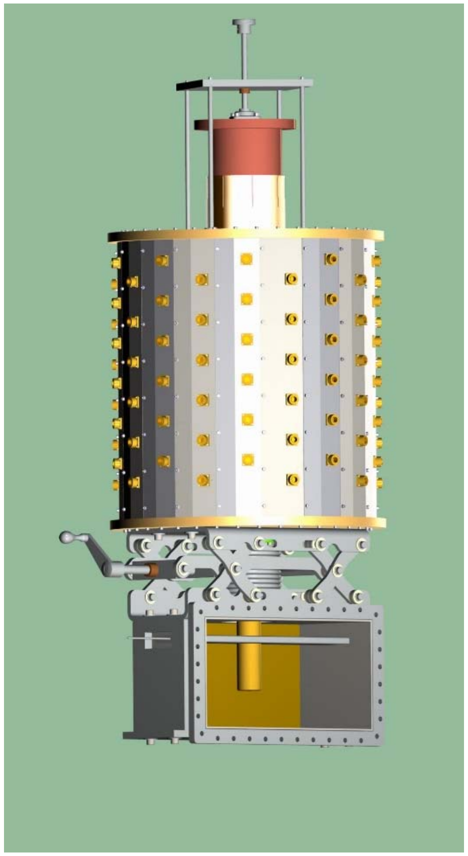
FREQUENCY RESPONSE AT OUTPUT COUPLER

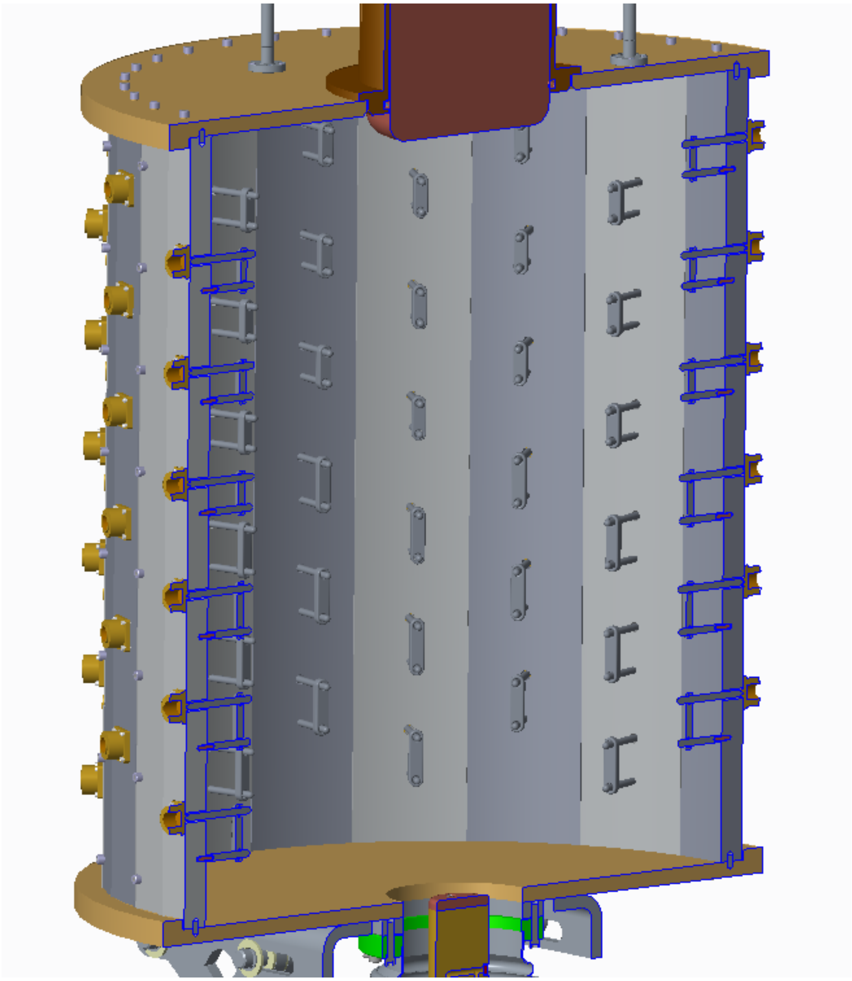


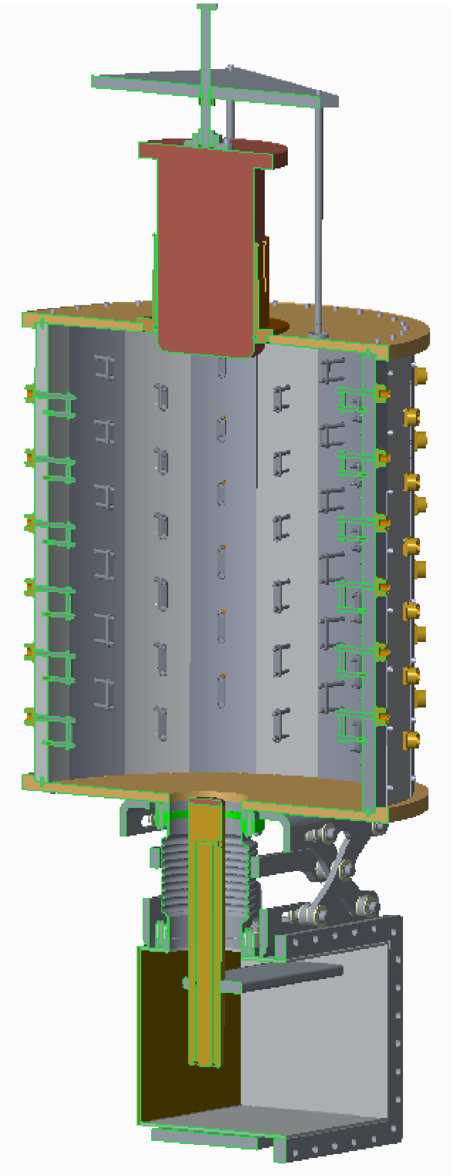
FREQUENCY RESPONSE AT INPUT COUPLERS



Output Cavity Combiner Design
-- CAD Figures



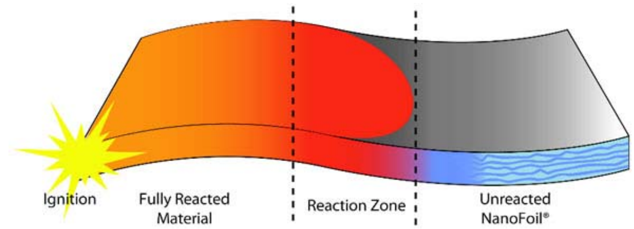


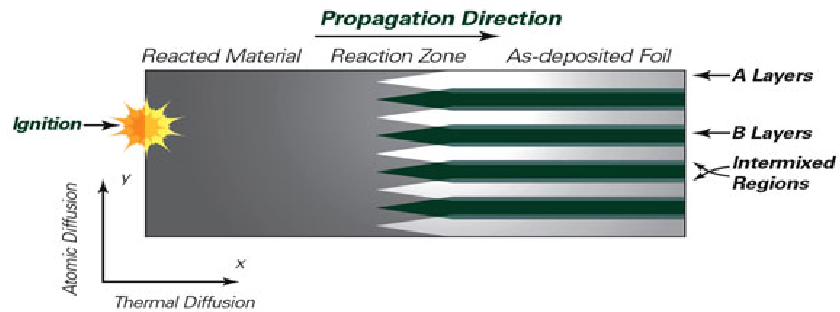


Nanobonding – K. Suthar
-- *An Alternative to Soldering?*

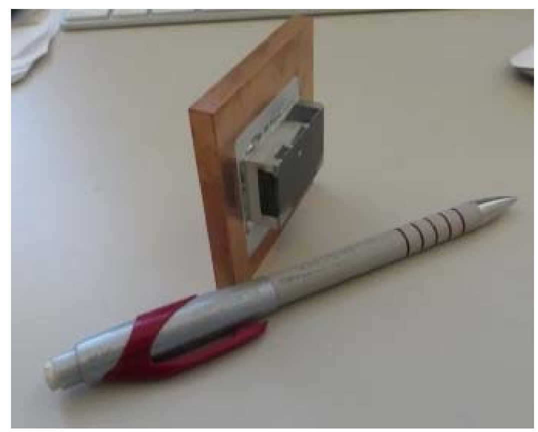
- Nanobonding: High-temperature exothermic reaction between nickel and aluminum in foil, triggered by electron flow
- Tin coating on foil melts during the reaction and bonds mating surfaces
- Exploring as an alternative to soldering for transistor package and circuit board

NANO FOIL:





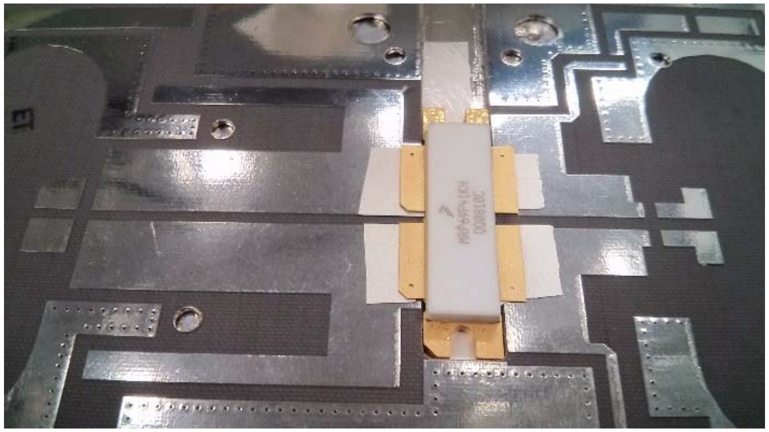
NANOBONDING OF TIN-COATED COPPER SLABS

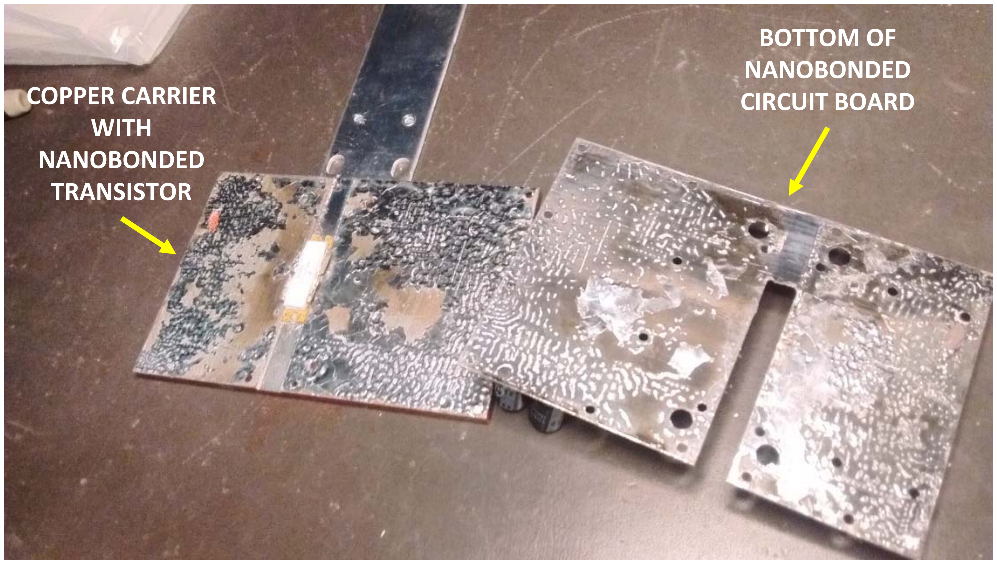


NANOBONDING OF SiC TO COPPER SLAB

Nanobonding -- K. Suthar
-- An Alternative to Soldering?

- Exploring as an alternative to soldering for transistor package and circuit board:



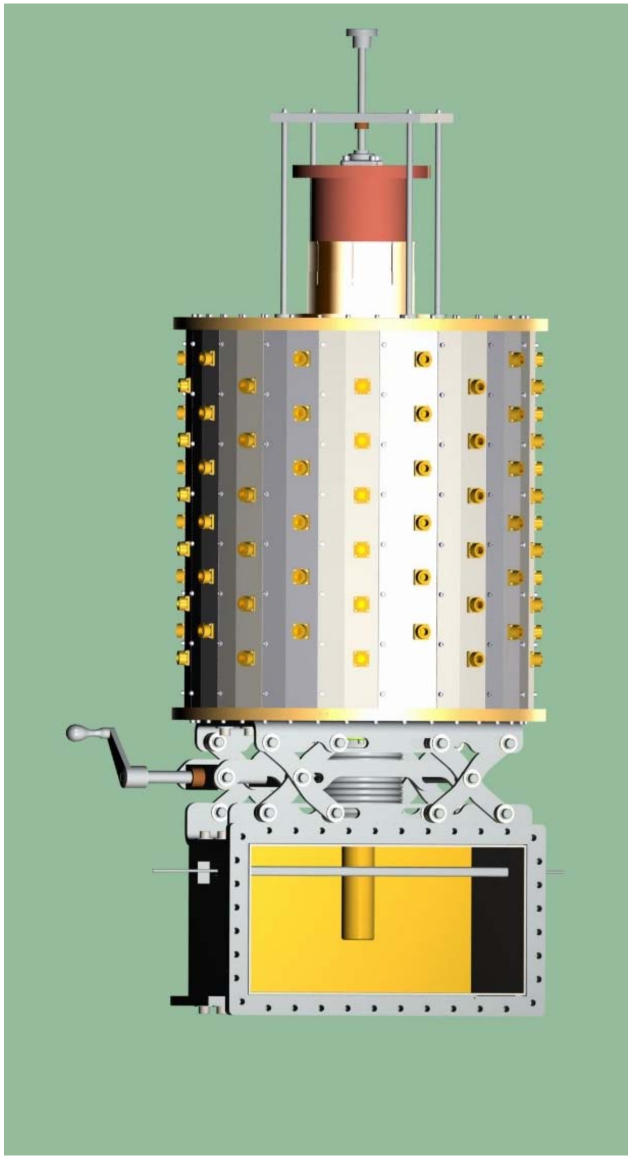


- Thermal and electrical compatibility tests underway

352-MHz Solid State -- *Summary*

- 12kW demonstration system will be assembled and tested in 2017

- Performance data will be used to implement design changes necessary to increase reliable output power to 100+ kW



- And now……….

Notable Failures!

RF1 Matching Transformer Fire
-- December 20, 2015

- 2.5MVA transformer steps down 13.2kV to 1,400 volts for thyristors in HVPS
- End-of-life insulation failure resulted in sustained arcing that progressed into a major fire
- Transformer and enclosure destroyed
- Replaced transformer with spare on hand, but had to emergency-order new enclosure
- Total repair time ≈ five weeks

Output Window Arcing on Thales TH2089A Klystron

- Damage detected during visual inspection at maintenance shutdown: *Burned screw seen on output transition*
- Further investigation revealed arcing damage to output center conductor
- Repair will be attempted