RF Developments at the Advanced Photon Source*

352-MHz Solid State RF
and
Klystron Tuning

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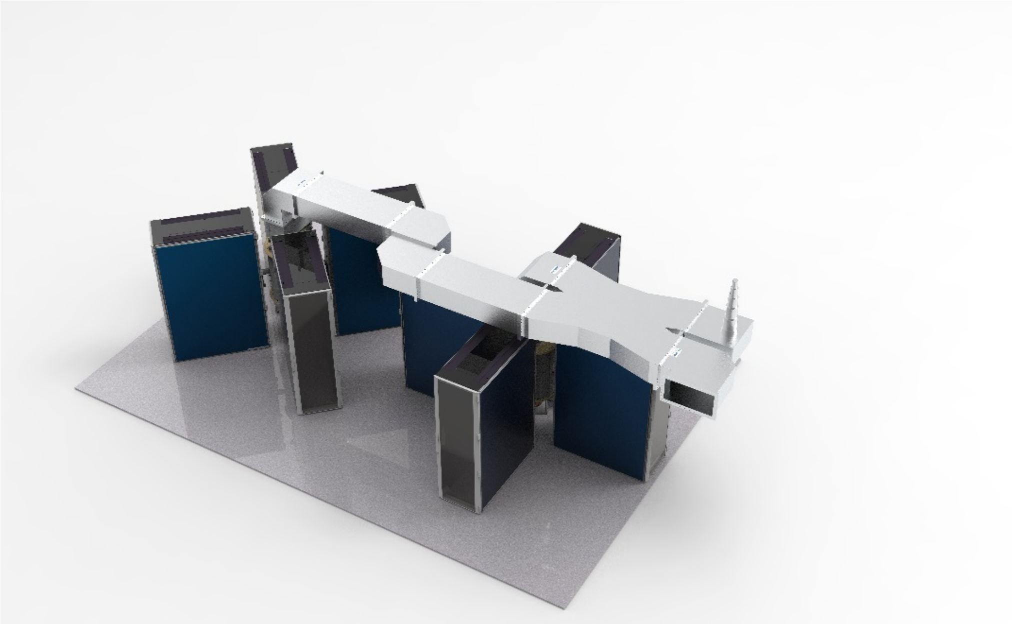
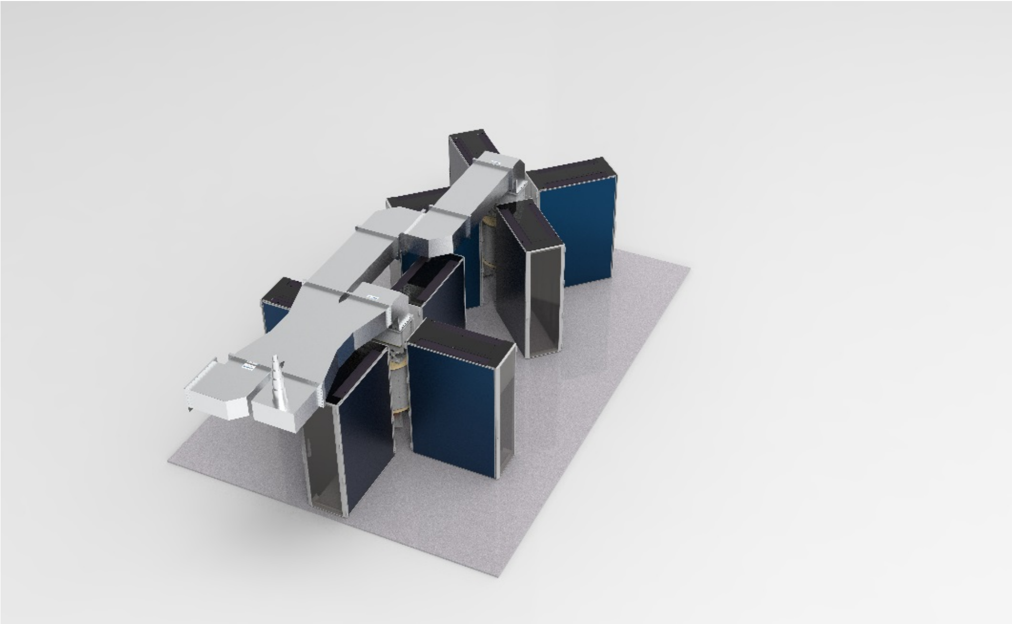
352-MHz Solid State Amplifier Development

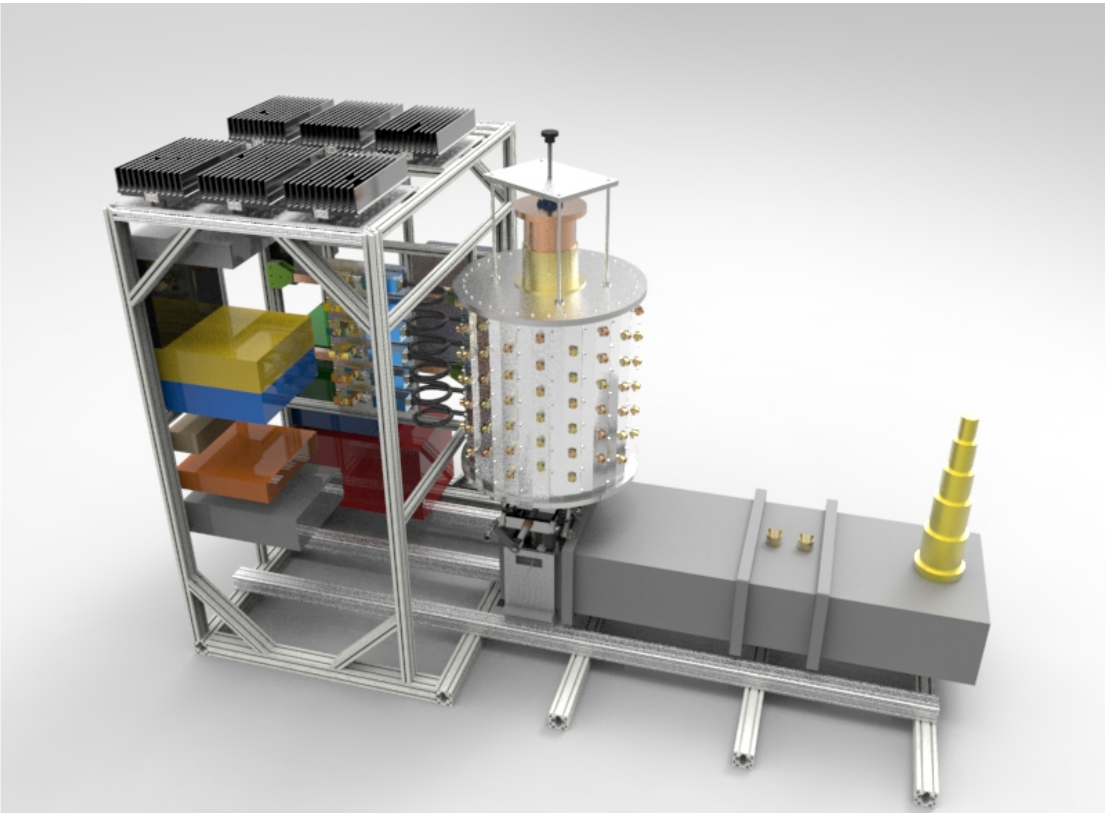
- Design goal is to produce a prototype 200kW system capable of driving one accelerating cavity
- Two 100-kW sub-systems will drive inputs of a final waveguide hybrid combiner
- 19-inch rack form factor adopted for amplifier modules to allow flexibility adapting to various output combiner devices
- The technical performance of combining cavity technology is presently being evaluated

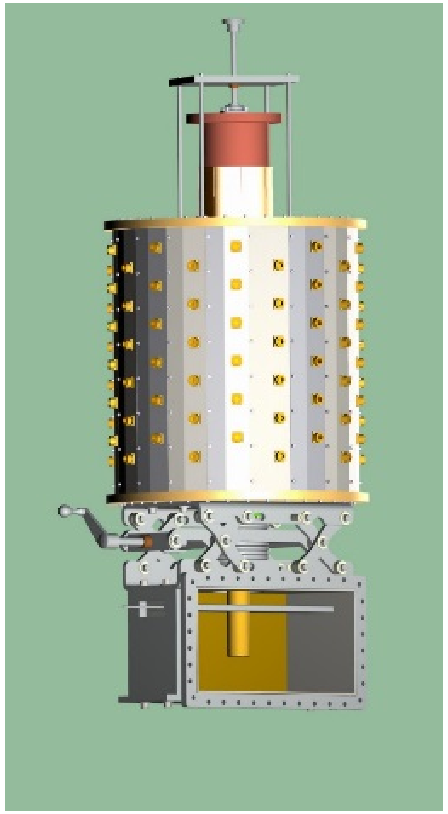




352-MHz Solid State Amplifier Development -- 12kW Demonstration System

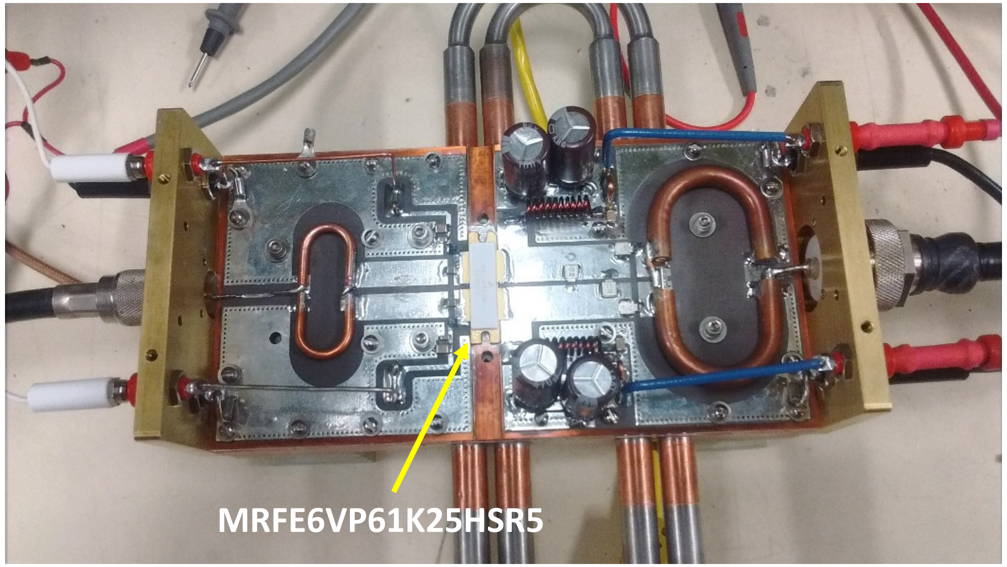
- Design and build 12kW system utilizing a 108-input combining cavity populated with six inputs
- Design and build six 2kW amplifier chains, including pre-driver and driver stages
- Demonstrate combining cavity operation to 12kW utilizing six 2kW inputs
- Demonstrate effectiveness of dynamic drain voltage control to optimize efficiency over wide dynamic range



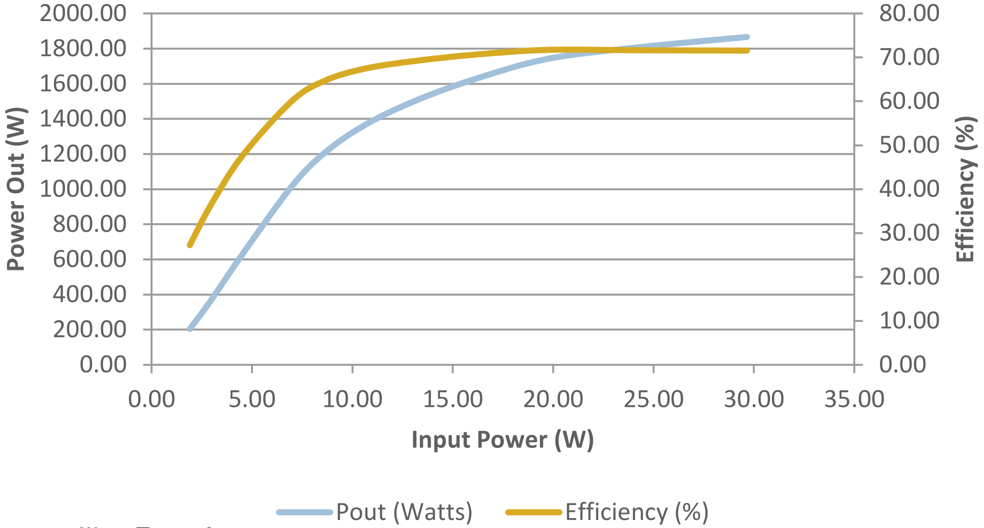


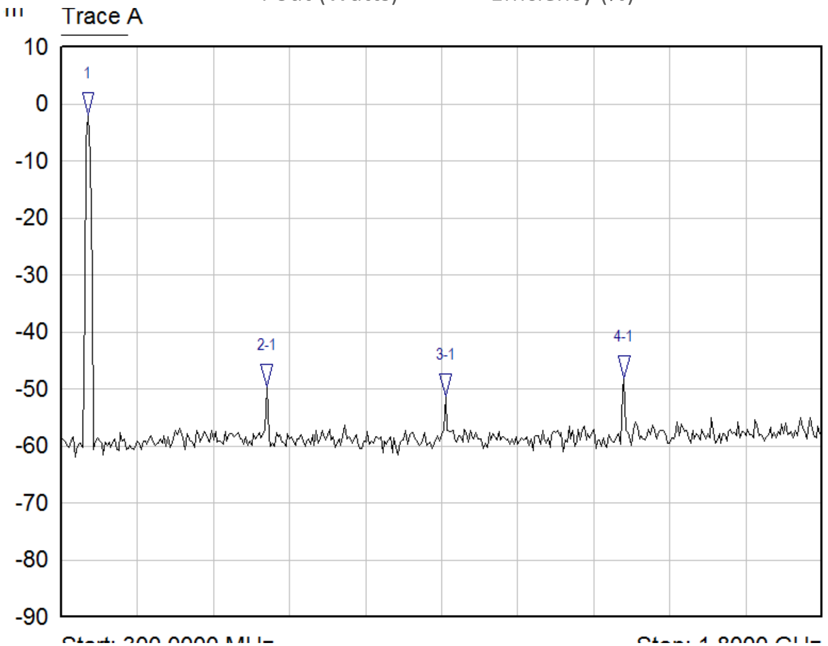
352-MHz LDMOS Amplifier Performance *– A. Goel*

-- 2kW CW Achieved with 1.25kW Part



Typical performance at Vd = 60 volts

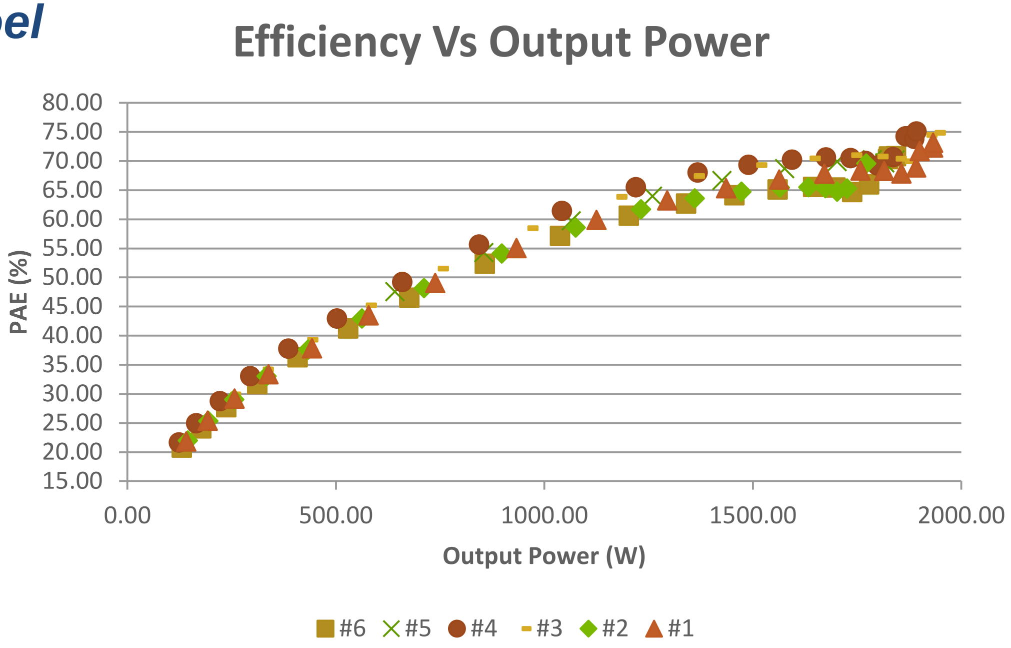


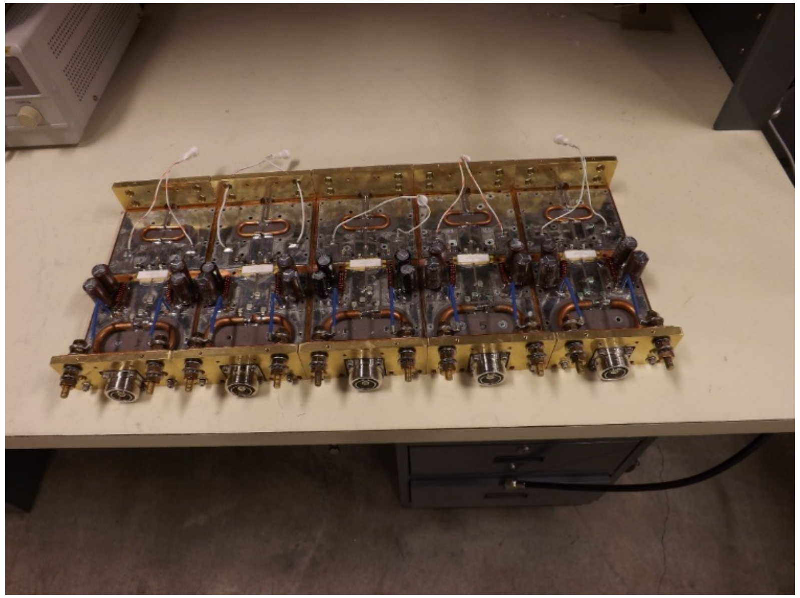


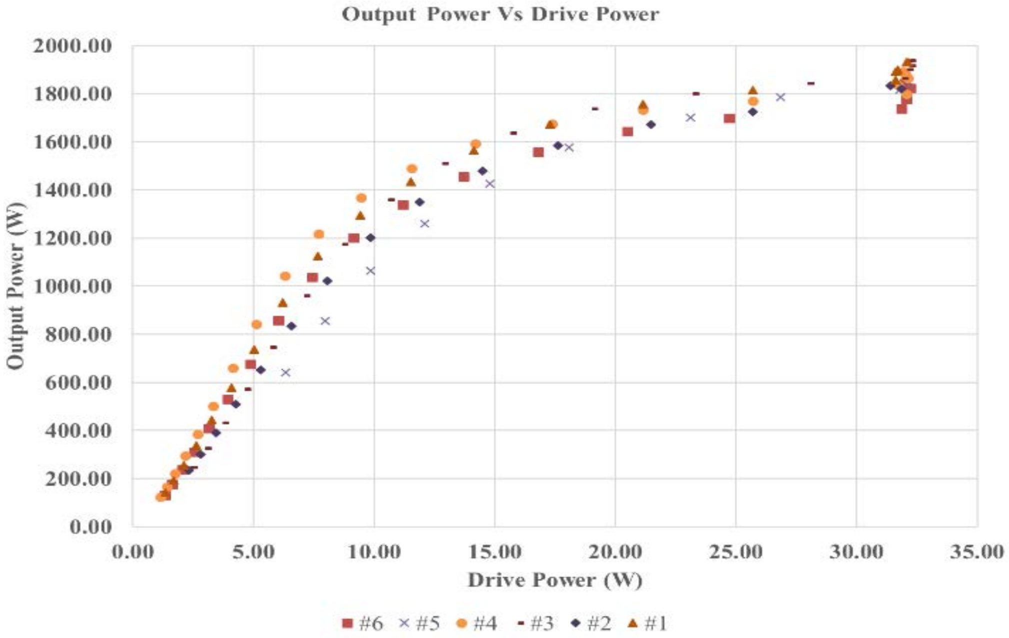
- Design completed and prototype constructed:
  → *Fine-tuned prototype produced*
  2,021 watts cw at 75.4% efficiency,
  with 18.6dB gain
- Very stable and continuous operation for 2 hours with no signs of thermal runaway or drift
- Harmonics are well controlled: at least -47dBC

352MHz/2kW Amplifier Production *– A. Goel*

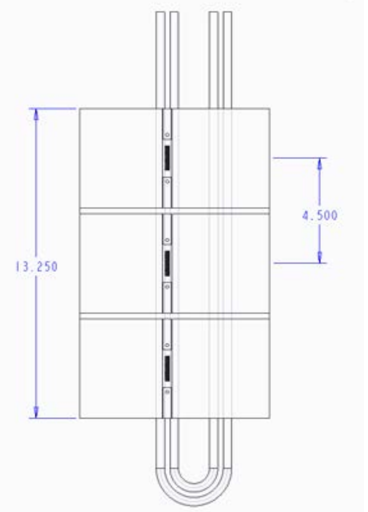
- Performance spread across the six working hand-built amplifiers:
  - 5.6% in power
  - 6.3% in efficiency
  - 1.4% in gain
  - 22% in power dissipation



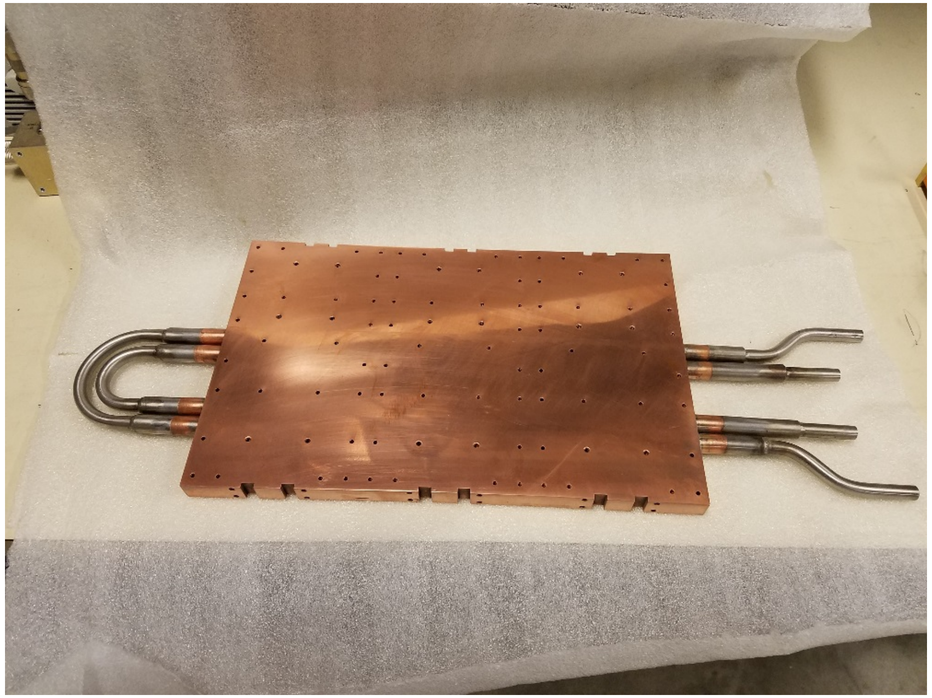




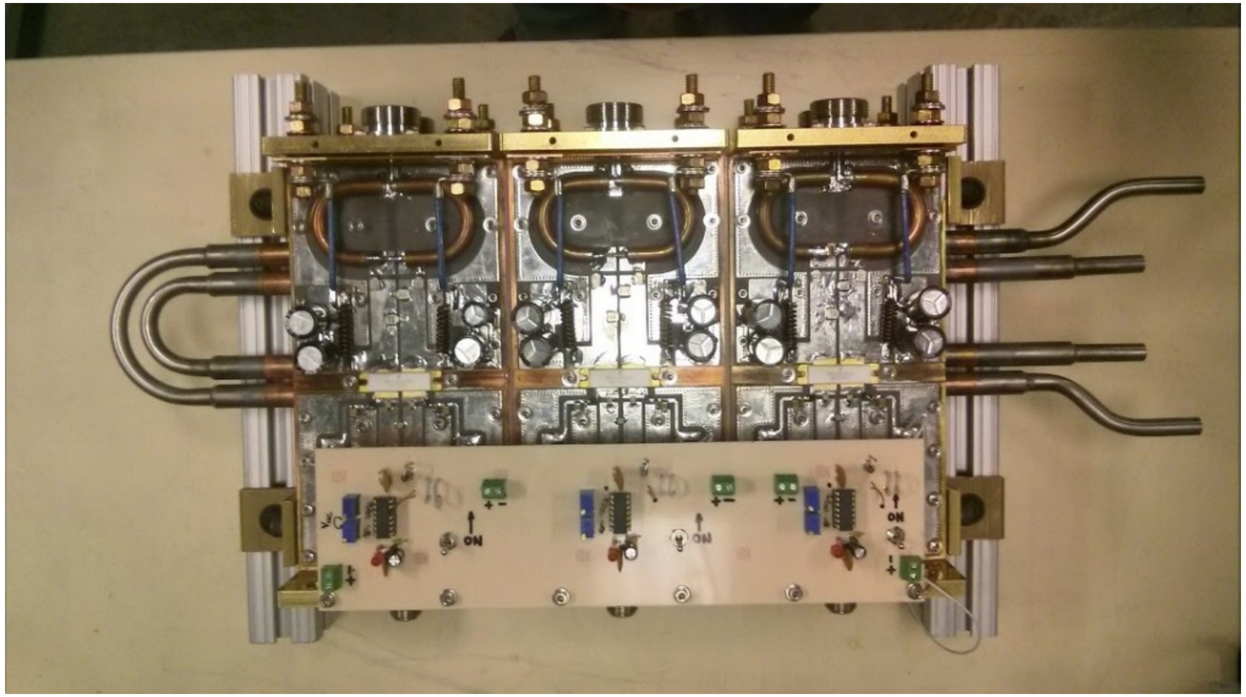
Six-Amplifier Cold Plate – *D. Bromberek*



- A water-cooled cold plate large enough to cool six 2-kW amplifiers (mounted on front and back) was designed using thermal simulation tools
- A production unit of the cold plate was produced for use on the 12kW demonstration system:



BARE COLD PLATE

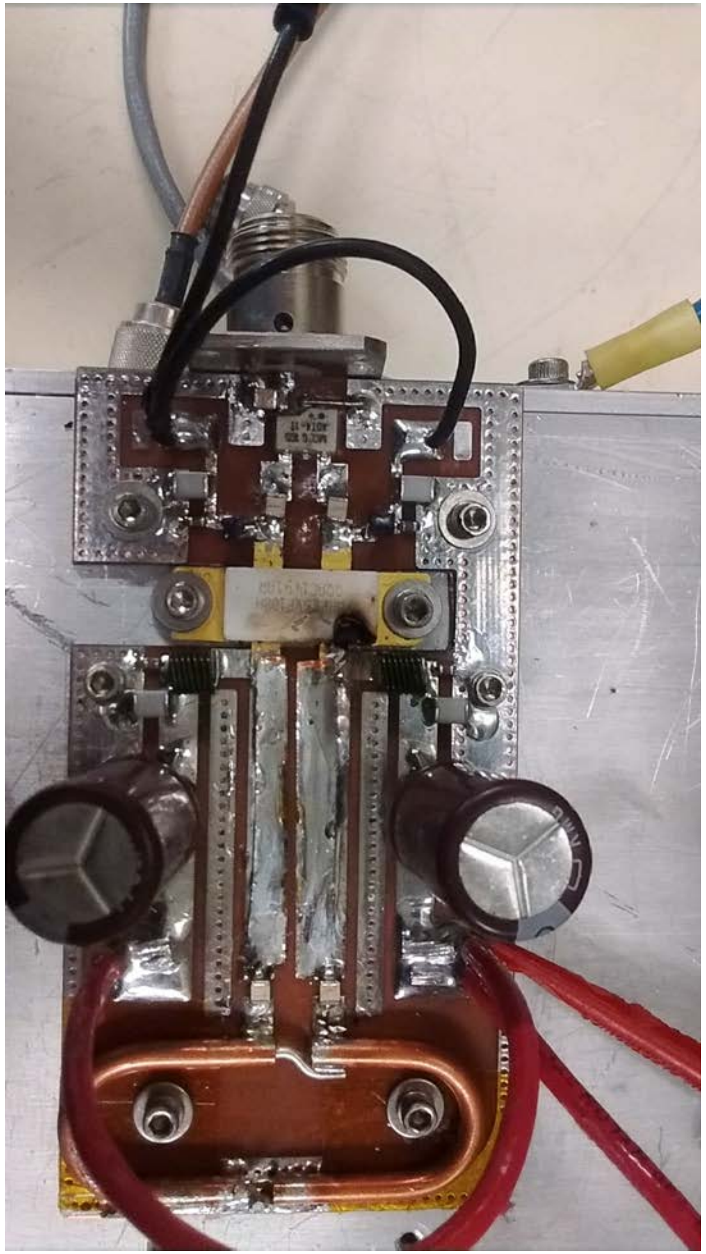


COLD PLATE WITH SIX 2kW AMPLIFIERS AND BIAS CIRCUIT BOARD

352-MHz Driver Amplifiers – *A. Goel*

-- Design – Construction --Testing

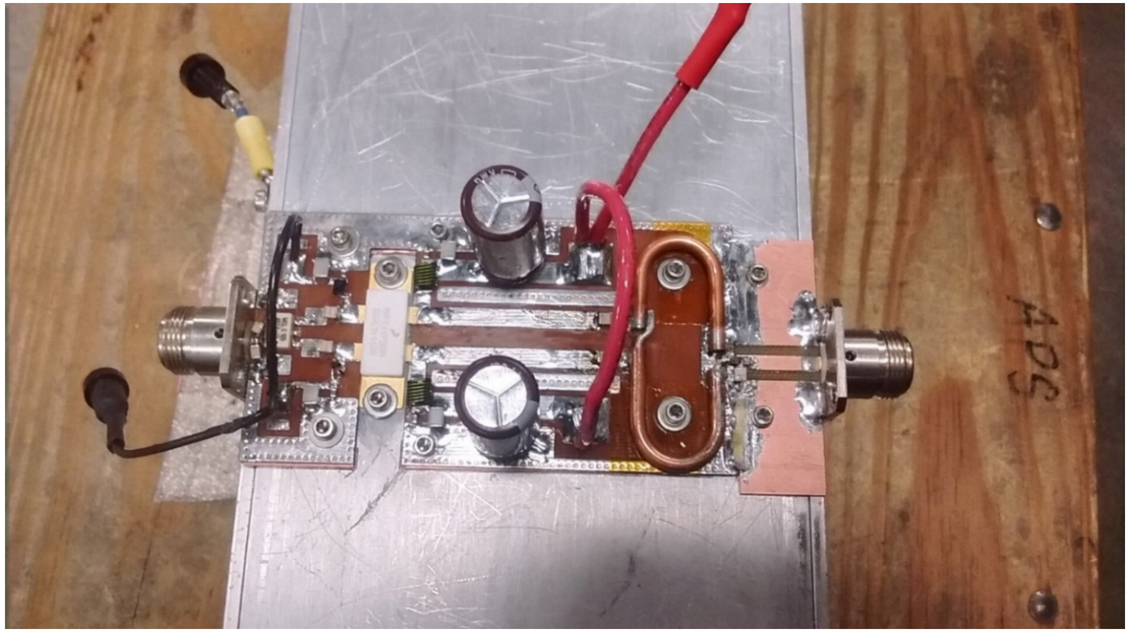
- Used MRFE6VP100H LDMOS part
- RF circuit simulation tools worked well on input side, but not so good on drain circuits – *and also did not anticipate the effect of a cold solder joint at the output connector*
- Copper-tape was used to get the drain circuit closer to where it needed to be



352-MHz Driver Amplifiers – *A. Goel*

-- Design – Construction --Testing

- Driver amplifier design was completed
- Design prototype achieved 100 watts output at 70% efficiency – *additional changes were implemented in the final design:*
  - → Input match improved by adding two additional capacitors
  - → 50Ω stripline daughter board added to output
- Construction of six production units was completed

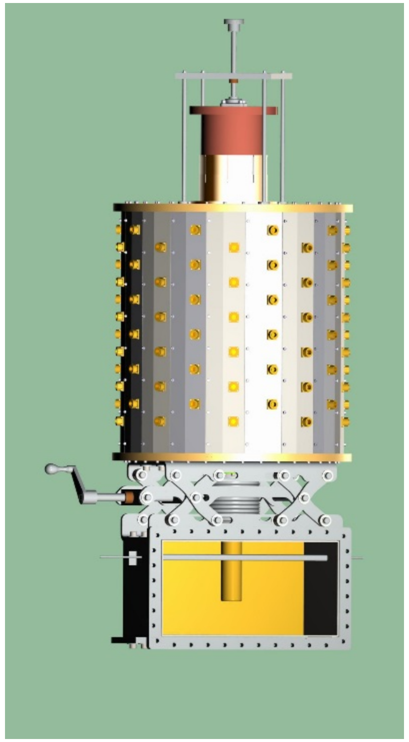


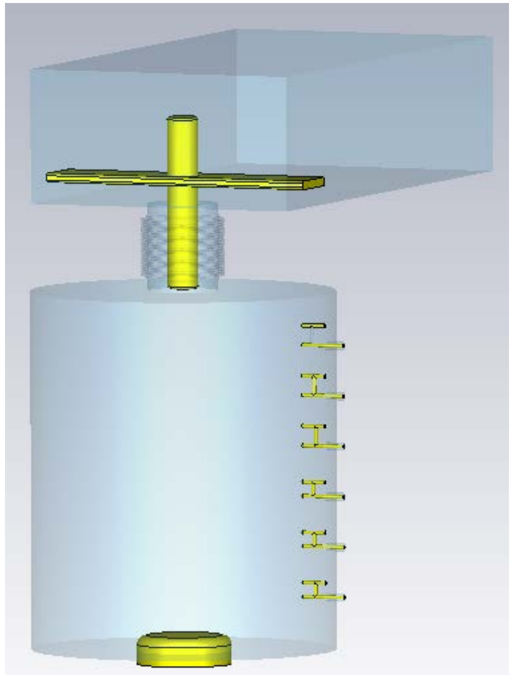
DESIGN PROTOTYPE DRIVER AMPLIFIER

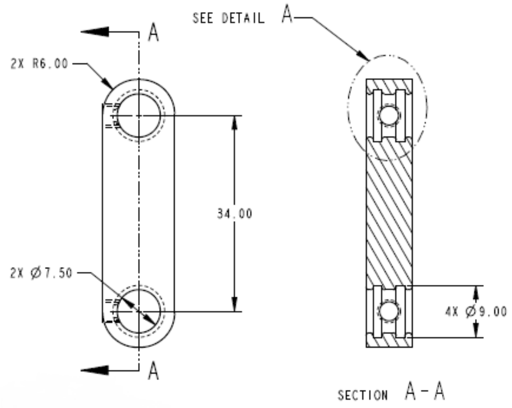
THREE PRODUCTION DRIVERS INSTALLED IN CHASSIS

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

- Design was completed on the prototype cavity, based on a 108-input, 200kW cavity combiner model
- E-probe output coupling direct to WR2300 waveguide
- Cavity is composed of 18 side panels, each designed for six rf input ports
- Manually-adjustable piston tuner on top plate
- Output coupling adjustable using support jack
- One 6-port panel was populated with input connectors and coupling loops for the 12kW test
- Cavity parts constructed from from silver plated aluminum
- All parts received from vendor by late December 2016
- Combining cavity assembly was completed in fall 2017

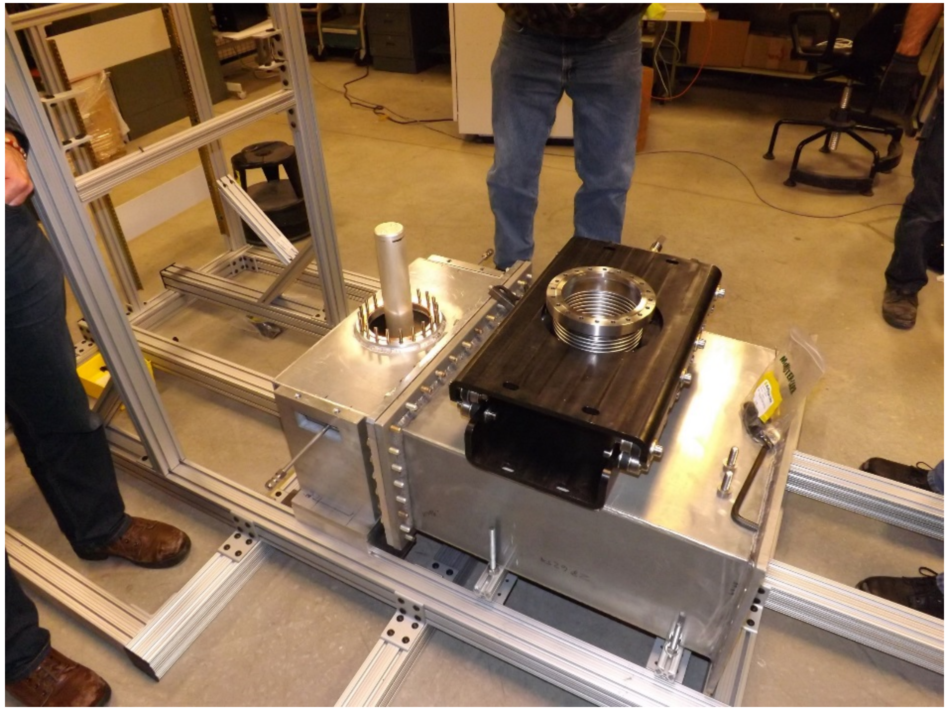






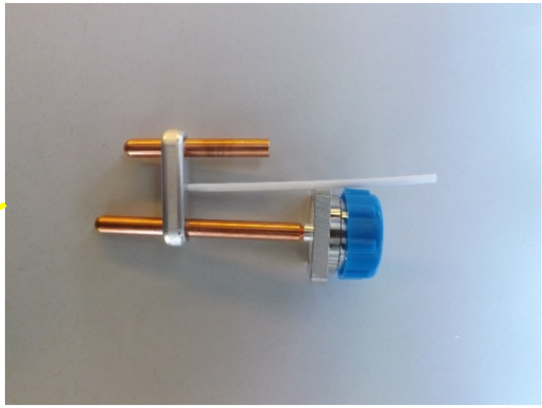
ADJUSTABLE INPUT COUPLING – SLIDING SHORTING BAR

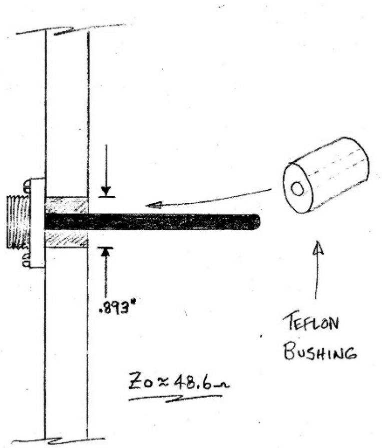
Output Cavity Combiner Assembly

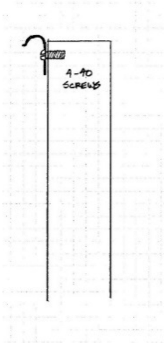


E-PROBE OUTPUT COUPLER AND WAVEGUIDE TRANSITION BEFORE ATTACHMENT OF CAVITY BASE PLATE

CAVITY INTERIOR SHOWING PANEL FINGERSTOCK AND ADJUSTABLE COUPLING LOOP

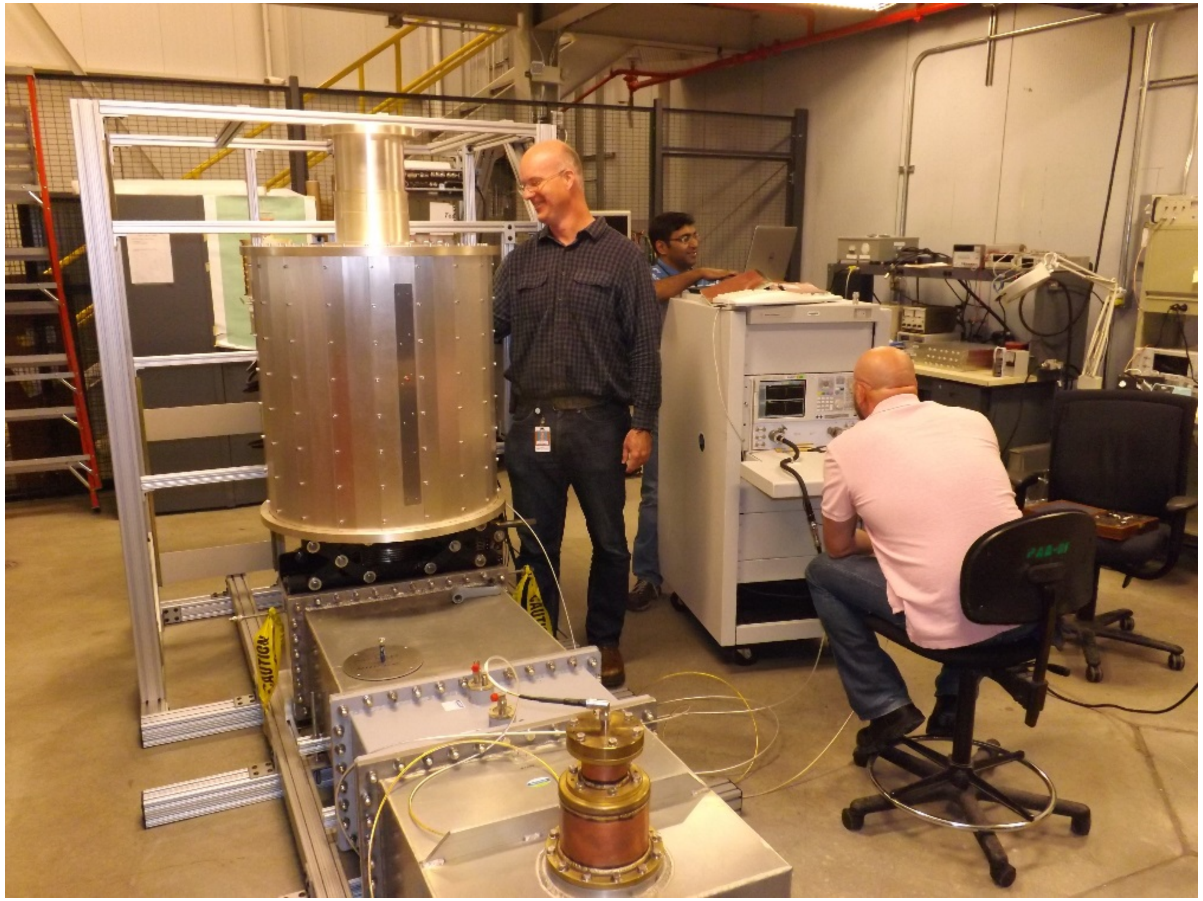






Output Cavity Combiner Assembly and Cold Test

INTERIOR VIEW OF COMBINING CAVITY DURING ASSEMBLY SHOWING SIX INPUT LOOPS ON ONE PANEL AND OUTPUT COUPLING PROBE AT BOTTOM CENTER

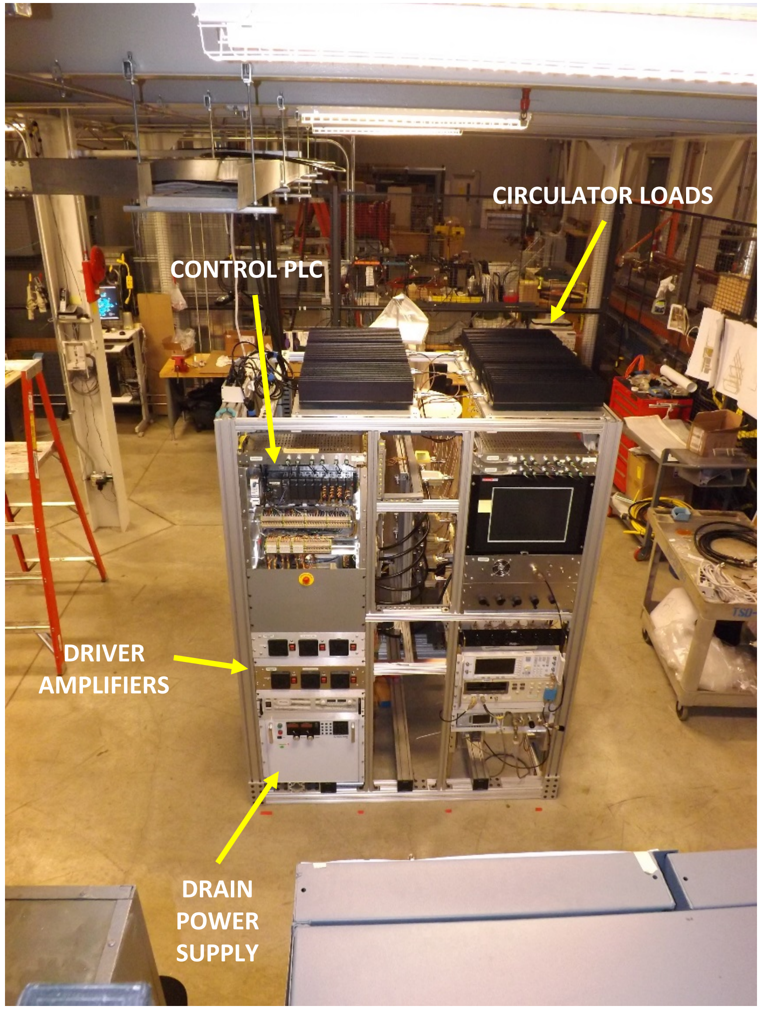


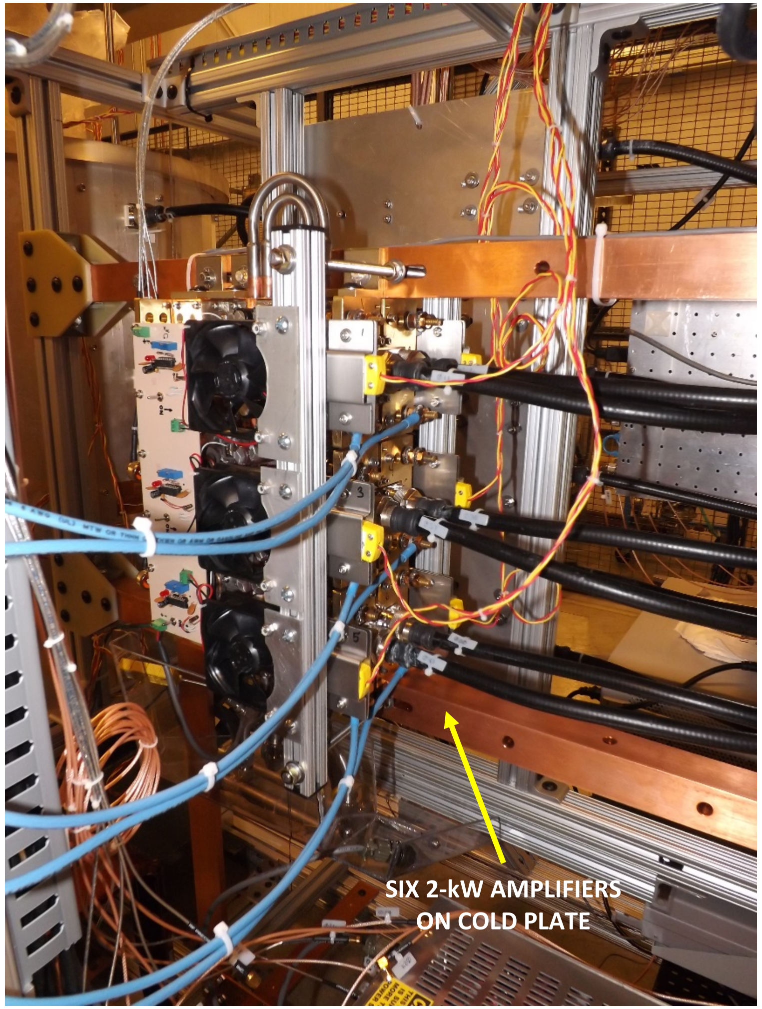
COLD TEST OF COMBINING CAVITY AFTER ASSEMBLY

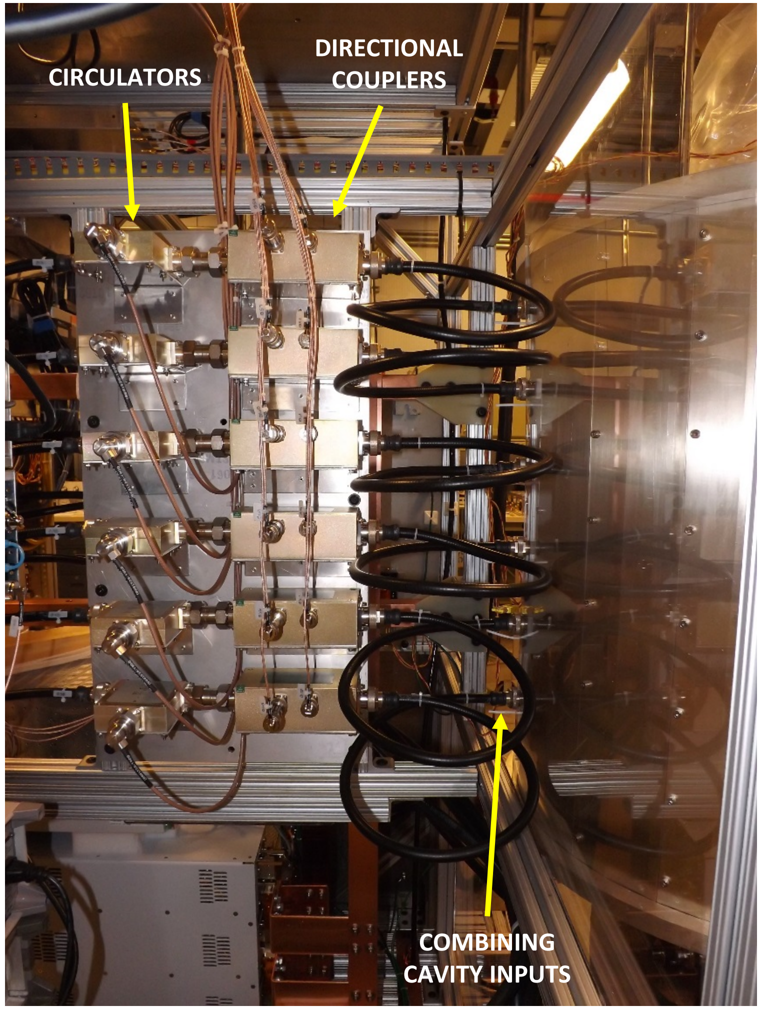
12kW System Construction

- Assembly and wiring was completed
- Electrical checkout and testing was completed
- Operation of system was started
- Data was taken to verify electrical and thermal performance of the amplifiers and combining cavity

12kW System Construction





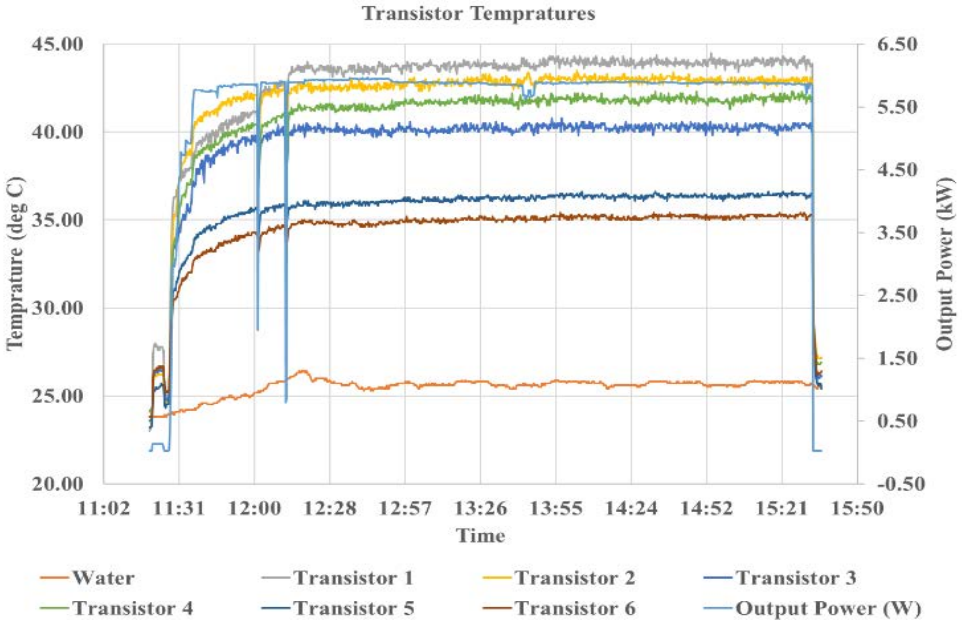


12kW System Operation

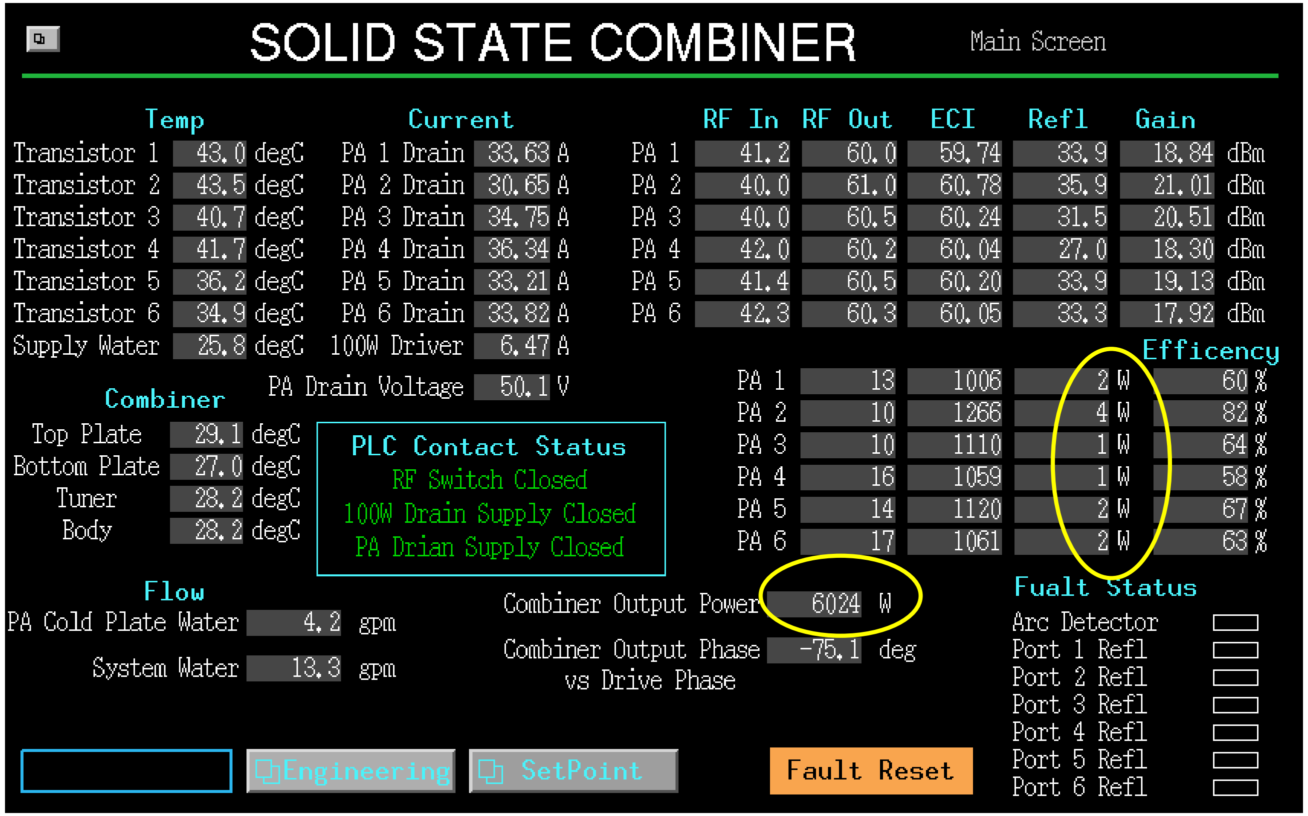
- Performed tests on combining cavity system at 6kW output power:

  → Verified good match at all cavity inputs

  → Verified thermal stabilization of all six 2kW amplifiers:



  → Cavity input phase optimized using mechanical phase shifters in amplifier chains – *no significant drift in rf phase was noticed up to 6kW output*



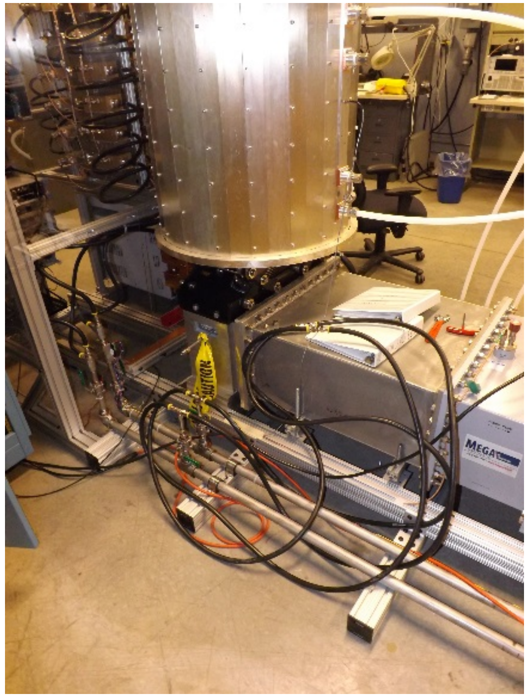
The combining cavity was checked for rf leakage at 6kW output → *All readings were below the instrument threshold of 0.01mW/cm²*

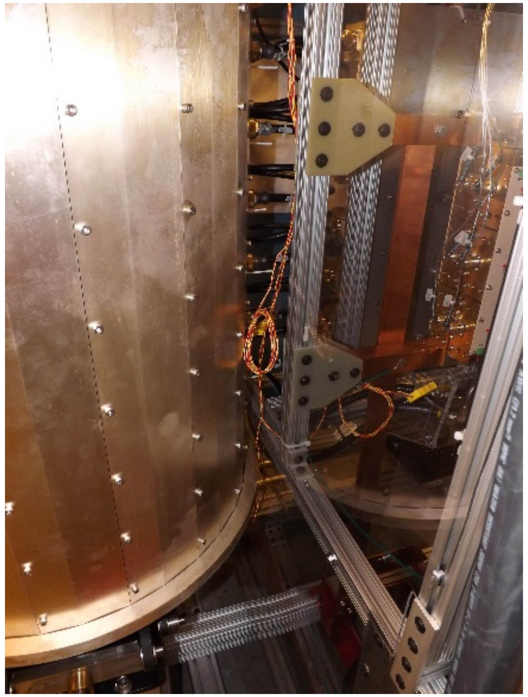
12kW System Operation *– D. Bromberek*

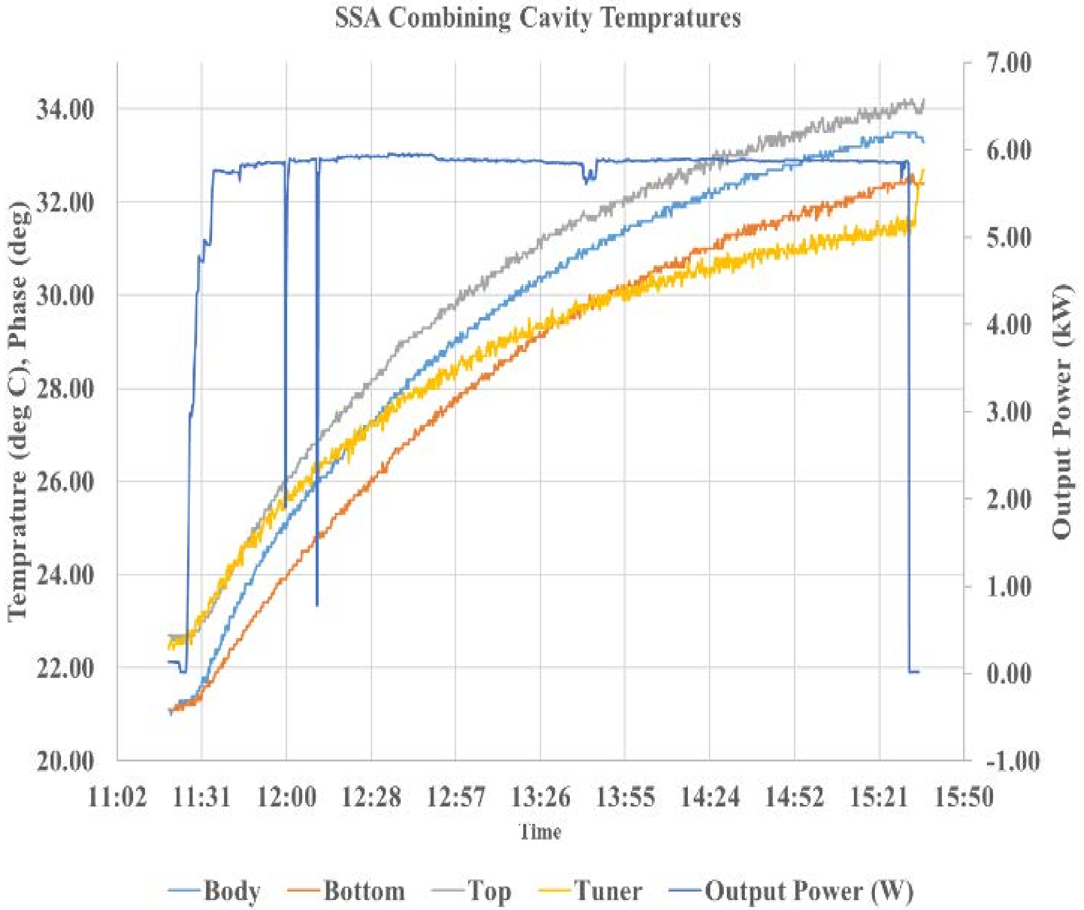
- Thermal measurements taken on combining cavity at 6kW output power over four hours:

  → Measurements indicate the need for water cooling

  → Work is underway to add water-cooled cold plates and additional thermocouples to the cavity:

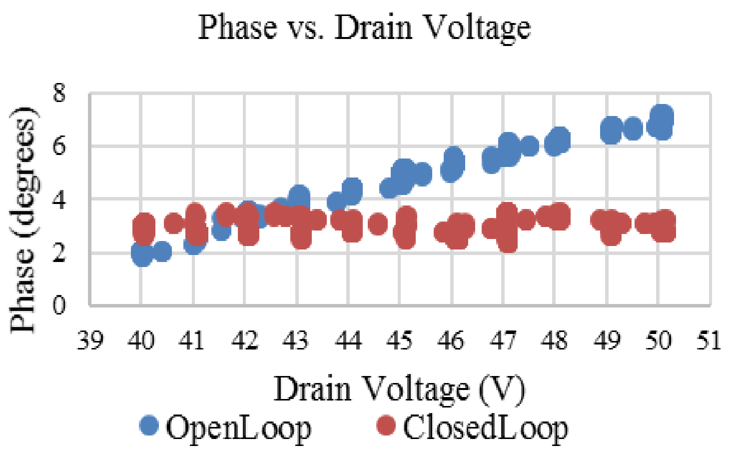


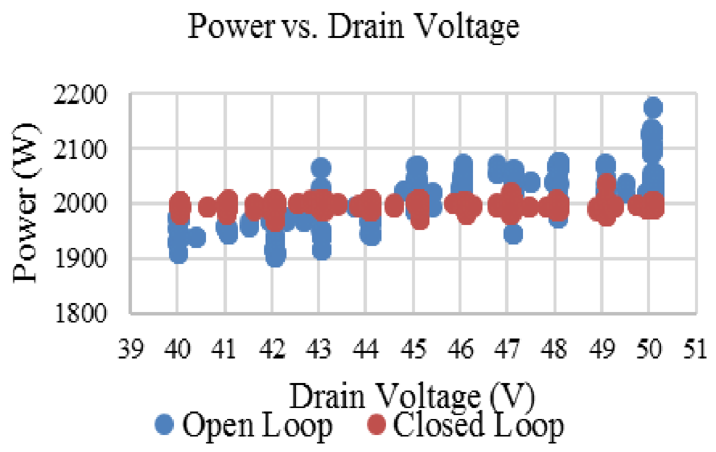




12kW System Operation *– T. Madden, T. Berenc*

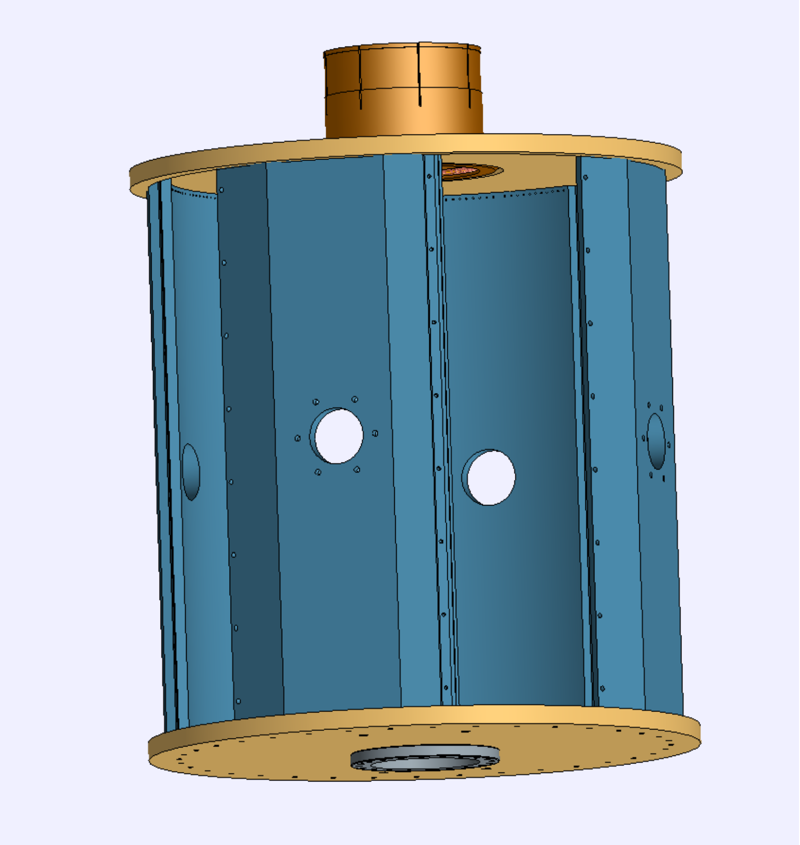
- The application of low-level rf phase and amplitude controls to the system was tested:
  - → Stable LLRF control was achieved
  - → Variations in drain voltage are effectively compensated:

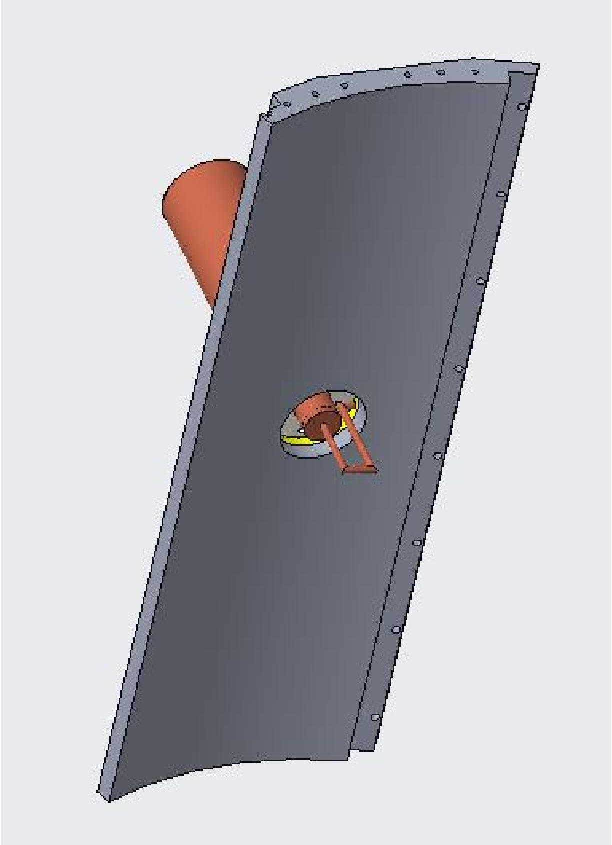




Combining Cavity R&D Plan

- Test three additional input configurations of the cavity at 30kW input power:
  - → Four-input: One input per panel,
    ~ 8kW per input
  - → Eight-input: Two inputs per panel,
    ~ 4kW per input
  - → Sixteen-input: Four inputs per panel,
    ~ 2kW per input
- Cavity input connectors will be 3-1/8-inch EIA flange
- Determine cavity thermal profile at 30kW
- Implement cavity tuning strategy and test effectiveness





Combining Cavity R&D Plan
– Test to 30kW CW

- Procurement process has started to purchase sixteen 352-MHz/2kW amplifier modules and necessary rf power combiners from industry
- Design effort is underway for new combining cavity side panels large enough to accept up to four 3-1/8-inch EIA flange connectors
- Design effort is underway for a 3-1/8-inch EIA-flanged input coupling loop
- 30kW combining cavity testing tentatively scheduled for late summer of 2019
- Dynamic drain voltage control for active efficiency optimization will be implemented and studied

Evaluation of New 1.8kW LDMOS Transistor – *A. Goel*

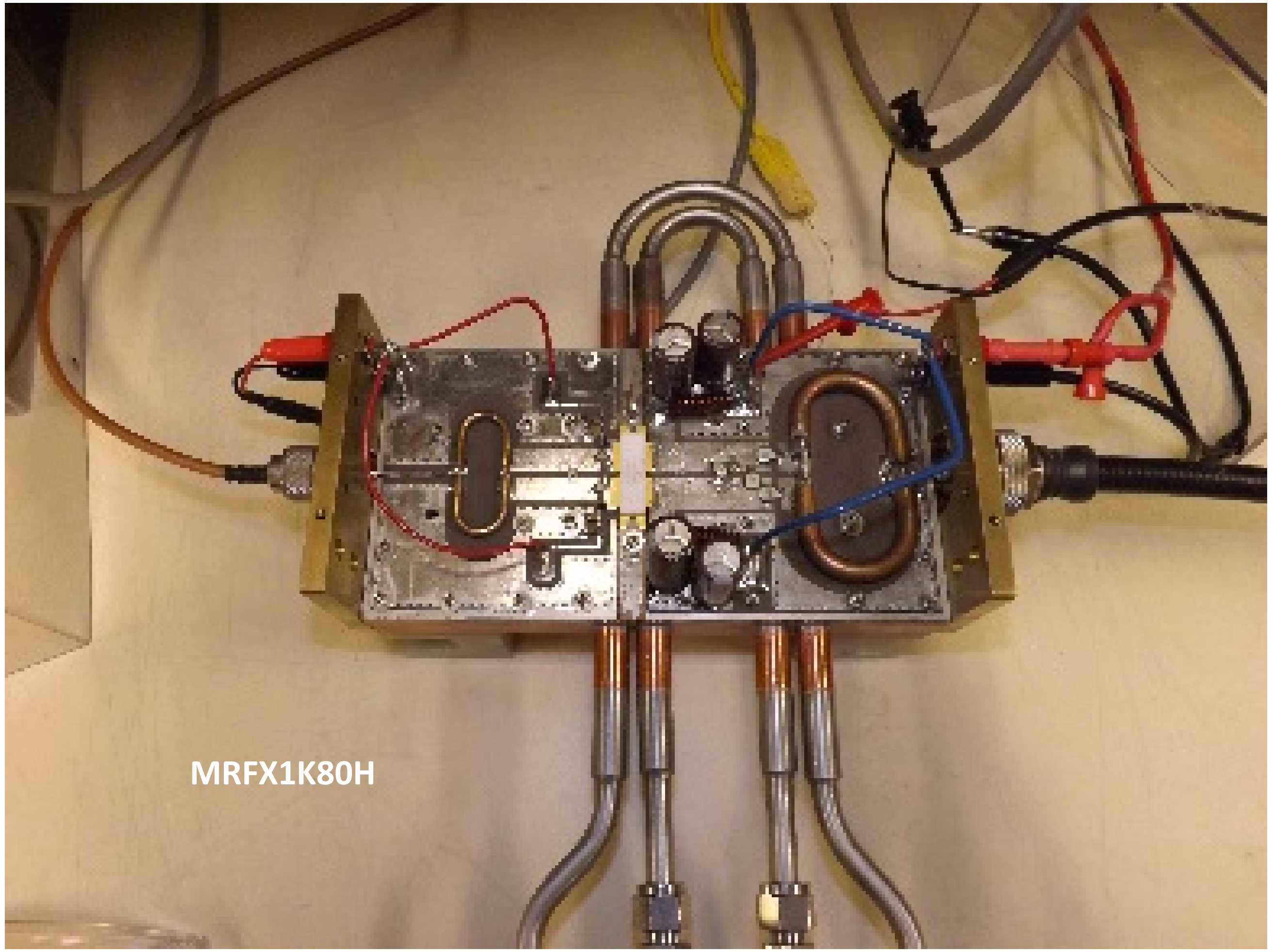
- Tested latest 1.8kW LDMOS transistor in the Argonne 352MHz/2kW amplifier circuit:

  → New part is not a “drop-in” replacement for the 1.25kW device used in the 2kW APS design

  → 1.4kW rf output achieved at 60% dc-to-rf efficiency, but instabilities at random frequencies were noted during tune-up process – *possibly related to large variations in drain-to-source capacitance over drain voltage range*

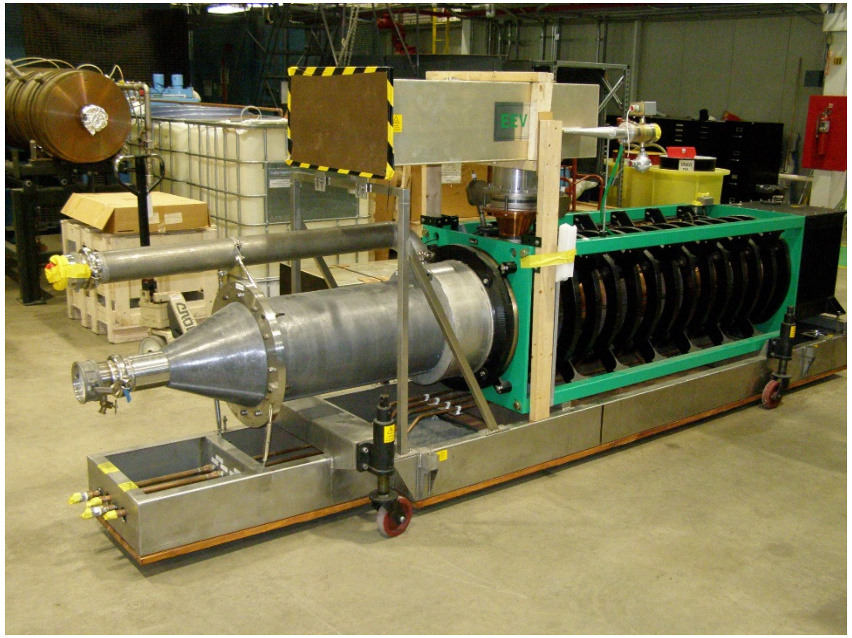
  → *Instabilities may make operation with dynamic drain voltage control problematic*

- Further evaluation of this part is planned



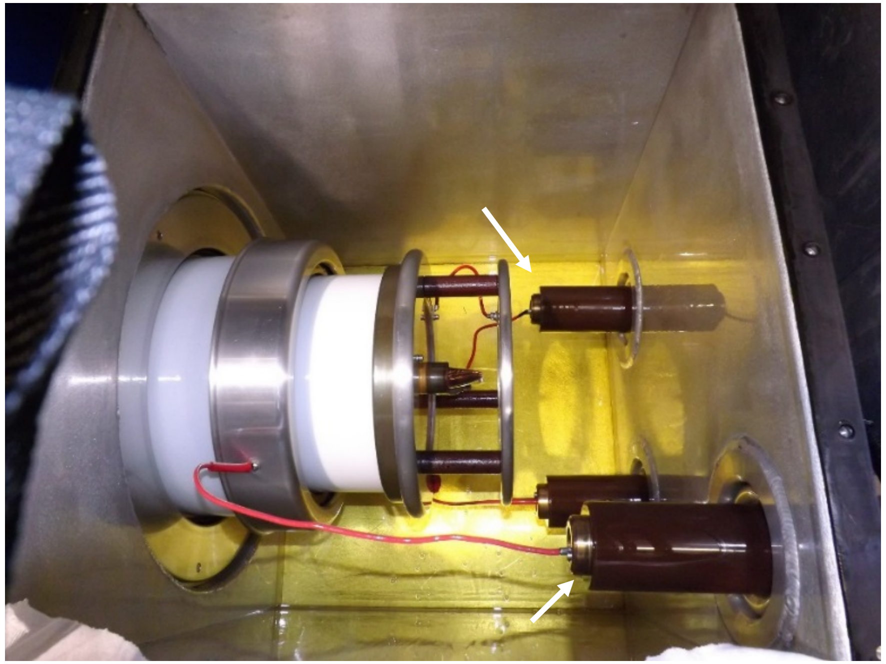
LANL 350-MHz/1MW Klystron Re-Tuning *– G. Trento*

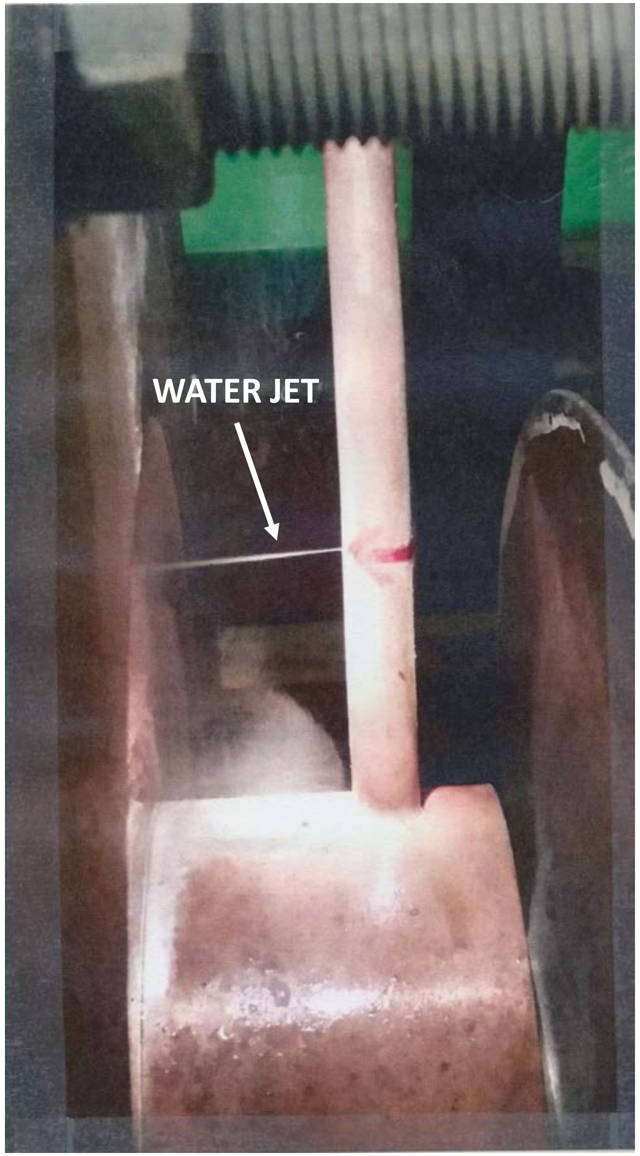
- Five klystrons received from LANL, two in 2010 and three in 2015
- All were factory-tuned for operation at 350.0MHz
- All were originally factory built in ~ 1997, but three had collectors replaced in 2004
- We initially tested each into a load at 350.0MHz at ≈ 500kW rf output ---- *all of them came to life with no problems or vacuum activity*
- As of June 18th – four successfully re-tuned to 351.93MHz, and the fifth is in progress

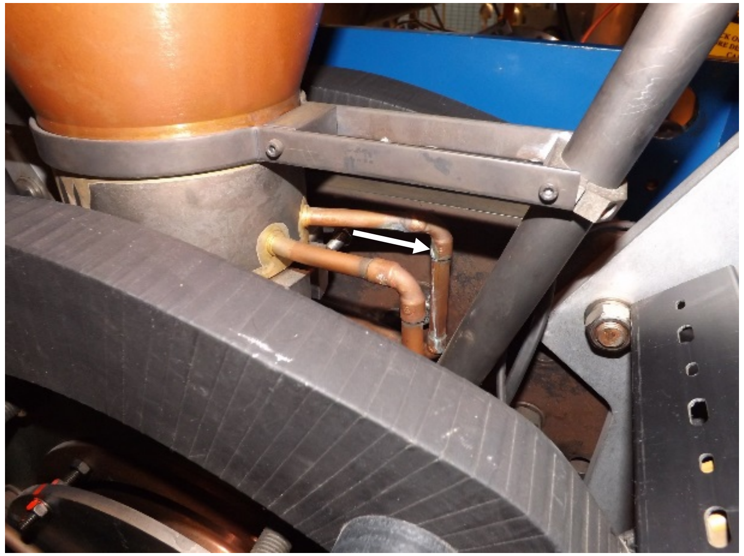


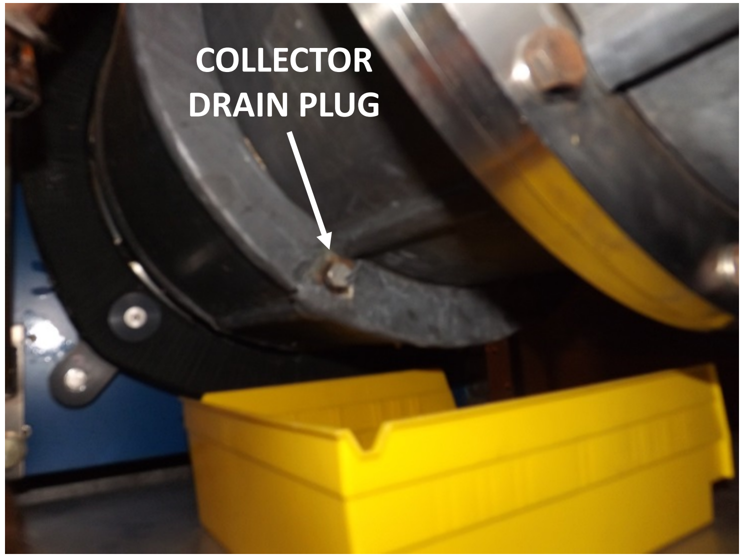
LANL 350-MHz/1MW Klystron Re-Tuning
– Minor Problems Encountered

- Small water leaks on collector drain plugs, and drift tube and output cavity tuning pipes
- Oil leaks from Pantak connector gaskets:









LANL 350-MHz/1MW Klystron Re-Tuning

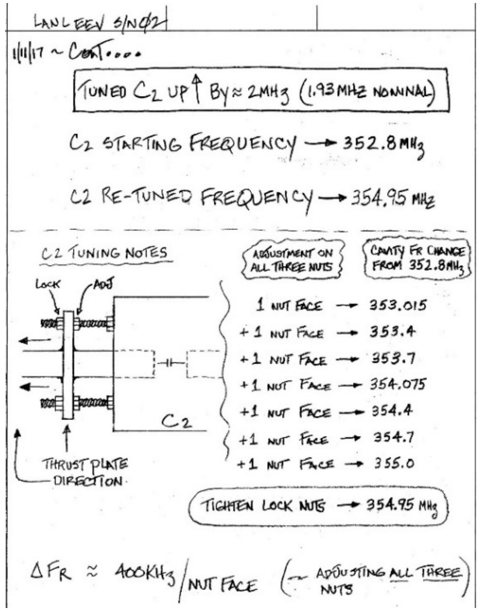
– *Cavity Tuning Mechanism*

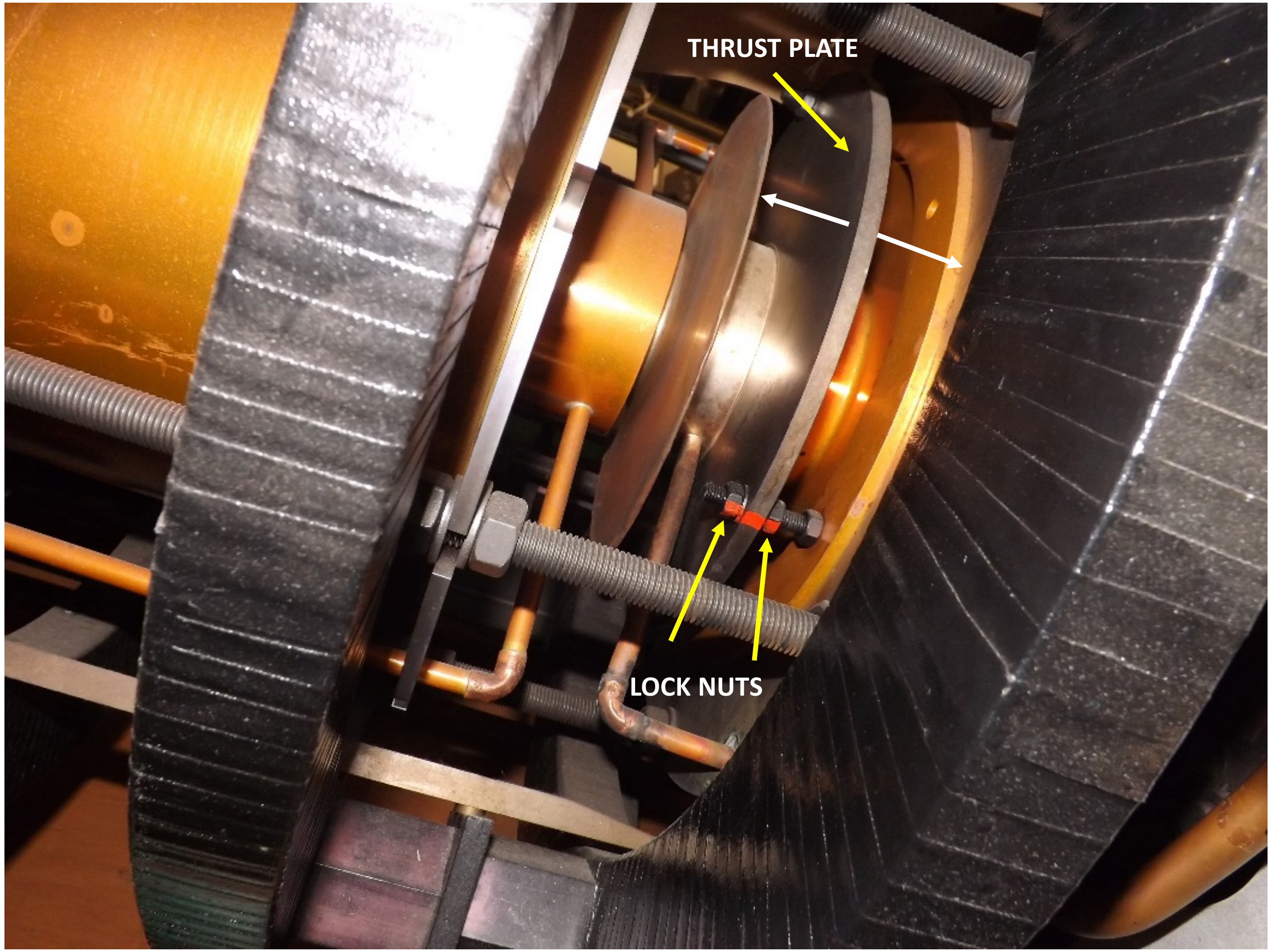
- Cavities are tuned by changing distance between cavity nosecones using a thrust plate and lock nuts

- Tuning rate is:

  → *~ 400kHz per "nut face" on 350MHz cavities*

  → *~ 600kHz per "nut face" on 700MHz cavity*





LANL 350-MHz/1MW Klystron Re-Tuning -- 350.0MHz to 351.95MHz *– Gian Trento*

- Cavities 1 and 2 are tuned ~ 2MHz up to achieve maximum rf gain, input cavity return loss, and center of operating bandwidth
- Cavity 3 (2nd harmonic) is tuned for maximum efficiency – tune up until you fall into "the hole" (2 x Fo), then tune down until efficiency recovers
- Cavities 4 and 5 are tuned approximately 2MHz up, peaked to result in ~ 2-3% efficiency improvement
- Output cavity was tuned slightly on first klystron to note the effect: ~ *1-2% efficiency improvement*

THE CAVITY TUNING PROFILE IS MEASURED USING A LOW-POWER RF SWEEP PERFORMED WITH 77kV/10A BEAM

LANL 350-MHz/1MW Klystron Re-Tuning
-- The Results

- LANL E2V s/n 005 -- Re-tuned on June 15th, 2011:

  → **87.6kV/17A**

  → **955kW rf output**

  → **64.1% eff**

  → ***Installed at RF1 in October 2016***

- LANL E2V s/n 01 -- Re-tuned on June 10th, 2011:

  → **87.5kV/17.03A**

  → **938.5kW rf output**

  → **62.9% eff**

  → ***Installed at RF2 in April 2016***

- LANL EEV s/n 02 -- Re-tuned on December 14th, 2017:

  → **80kV/15.39A**

  → **645kW rf output**

  → **52.3% eff**

  → ***Lower rf gain than expected – will re-tune when installed in a socket***

- LANL EEV s/n 01 -- Re-tuned on April 6th, 2018:

  → **80kV/15A**

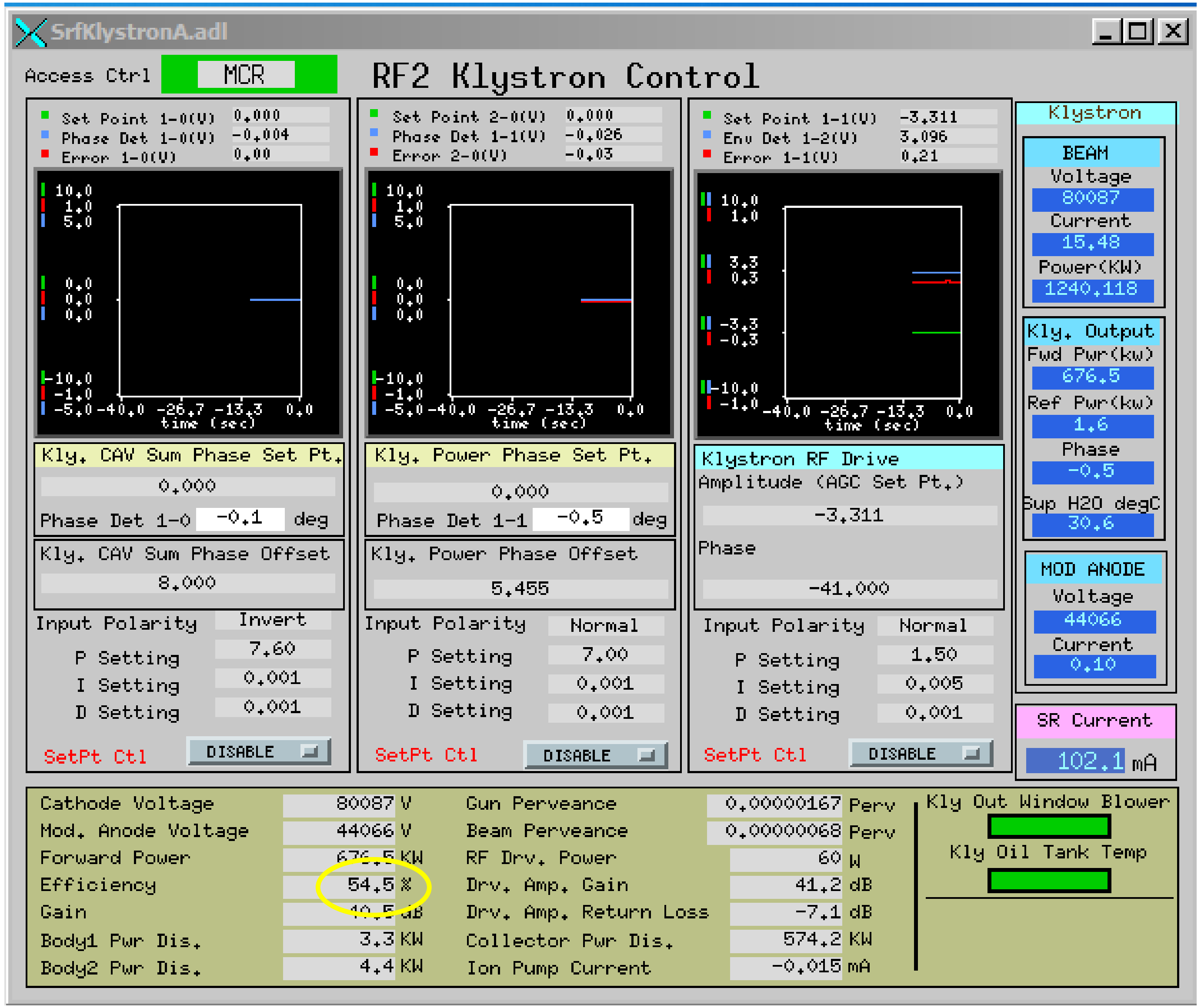
  → **651.8kW rf output**

  → **54.2% eff**

- LANL EEV s/n 04 – *Re-tuning in progress*

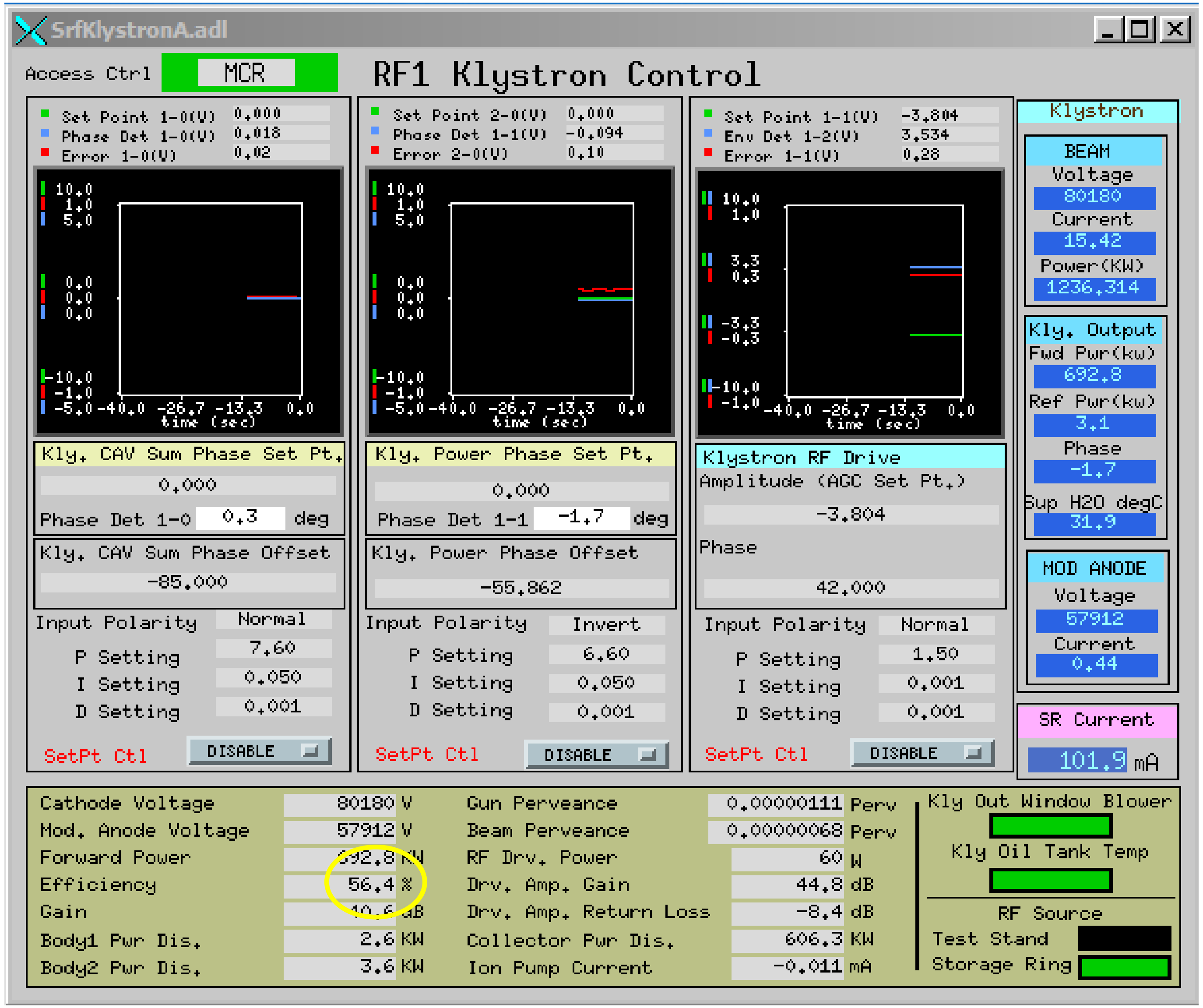
Re-Tuned LANL 352-MHz Klystrons in Operation

- LANL E2V n. 01 in RF2 socket on June 7, 2018 -- with 102.1mA stored beam
- Efficiency in normal range: 54.5%
- Operates at 80kV with no instability issues
- Low body losses
- No vacuum activity
- So far, so good



Re-Tuned LANL 352-MHz Klystrons in Operation

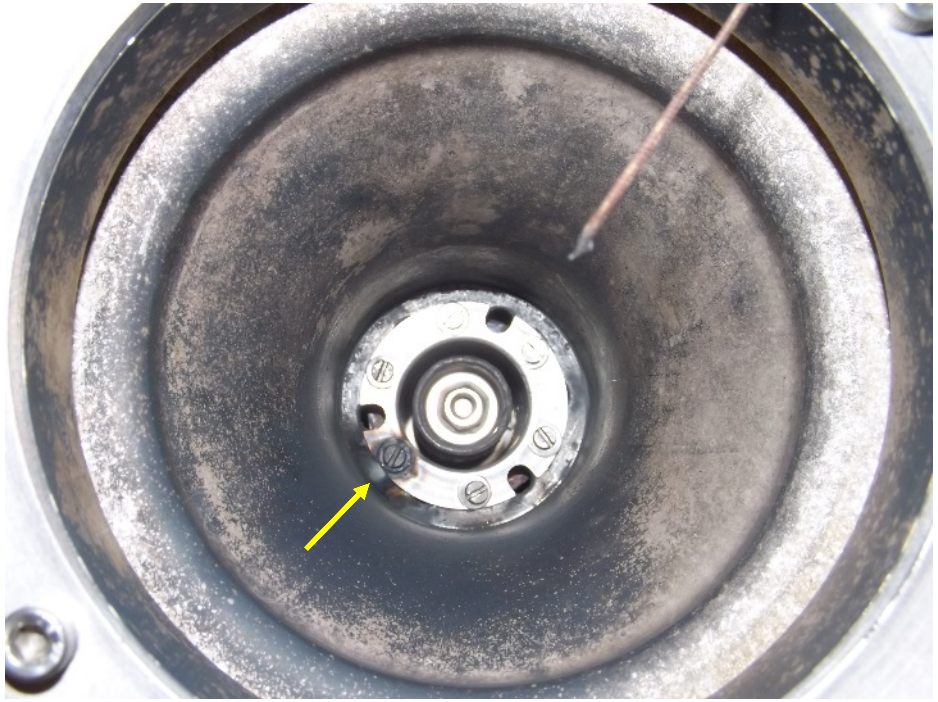
- LANL E2V n. 005 in RF1 socket on June 7,2018 -- with 101.9mA stored beam
- Efficiency in normal range: 56.4%
- Operates at 80kV with no instability issues
- Low body losses
- No vacuum activity
- Difference in gun perveance to be investigated
- Again…..so far, so good



Repair of Burned Klystron RF Output Conductor

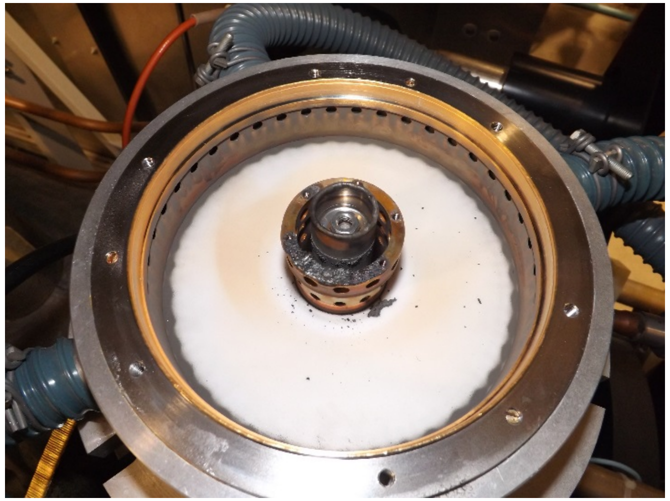
-- D. Bromberek

- Damage was detected during a visual inspection – *A burned screw was noticed on output transition*

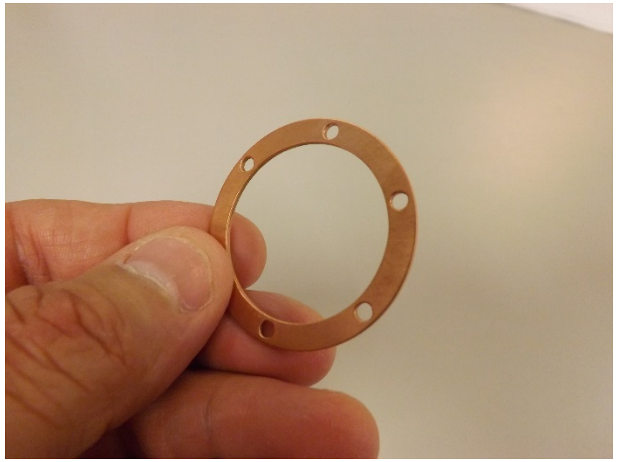


- The klystron has ~ 40k hours on it, and was running ok at the time of this failure – *the repair is worth a try*

- Further investigation revealed arcing damage to output center conductor:



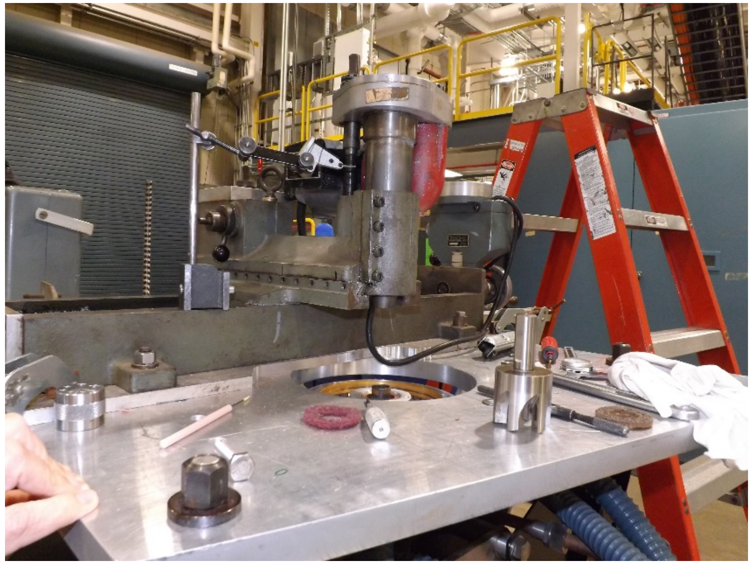
- Repair involved milling away the burned portion of the center conductor and inserting a machined spacer



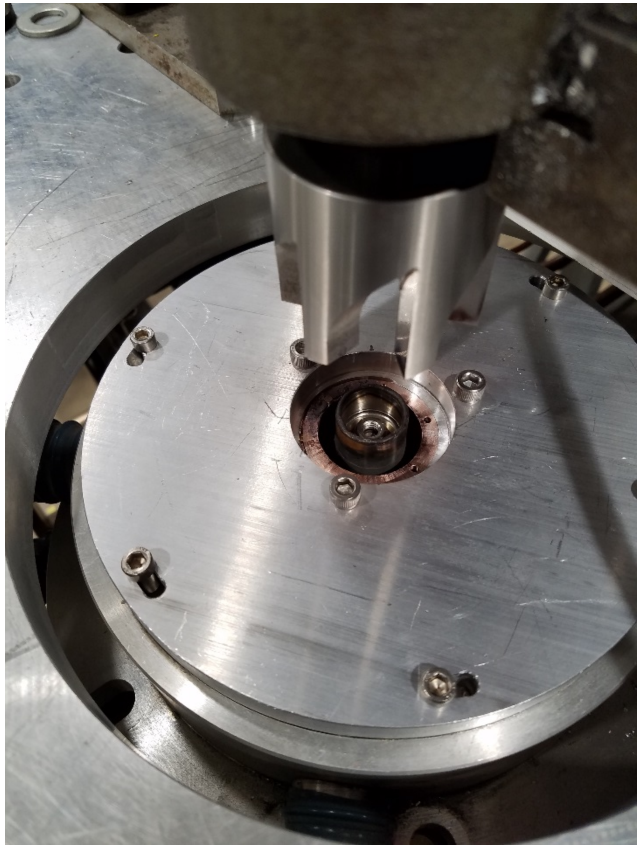
Repair of Burned Klystron RF Output Conductor
– D. Bromberek

- A custom milling tool was created to remove the burned surface and provide clearance for vacuum seal on center conductor →

- A milling machine and support platform was mounted on the klystron:



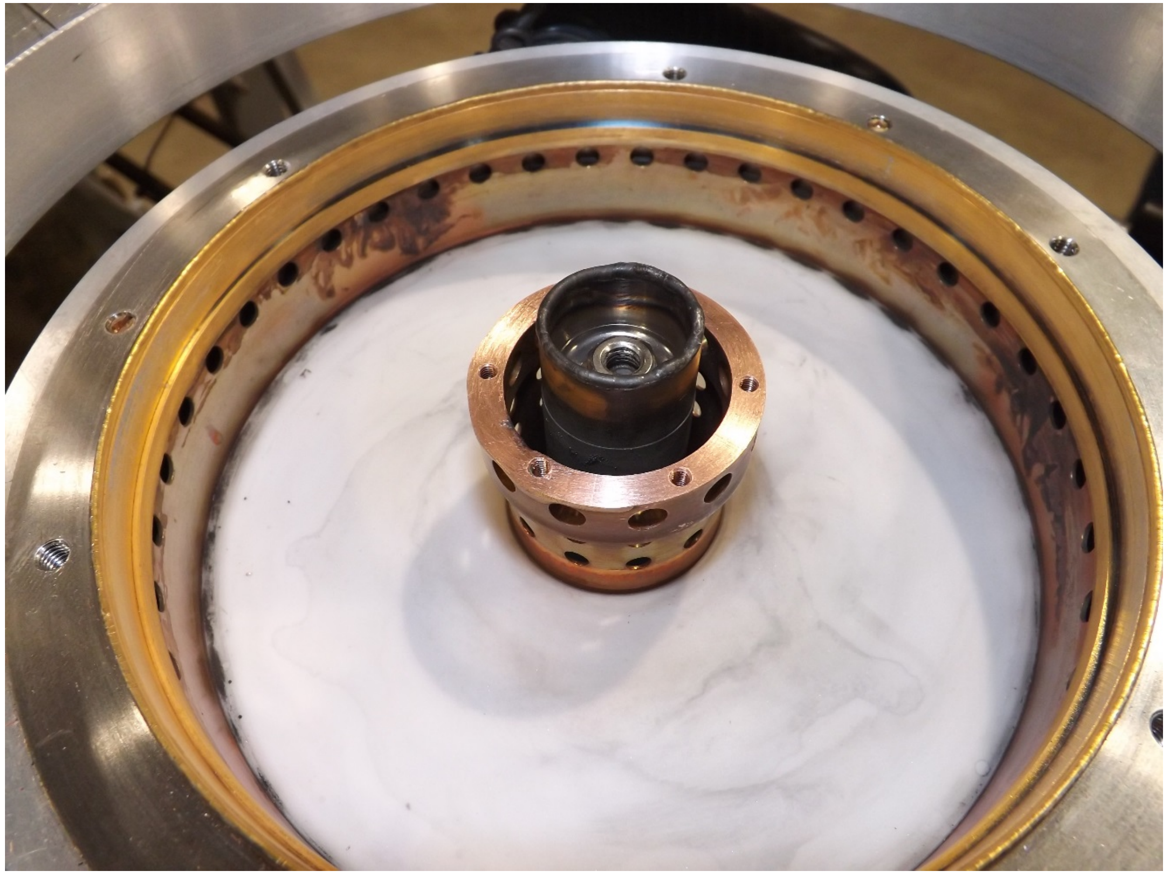
- A protective cover was placed over the ceramic output window during the milling process →



Repair of Burned Klystron RF Output Conductor

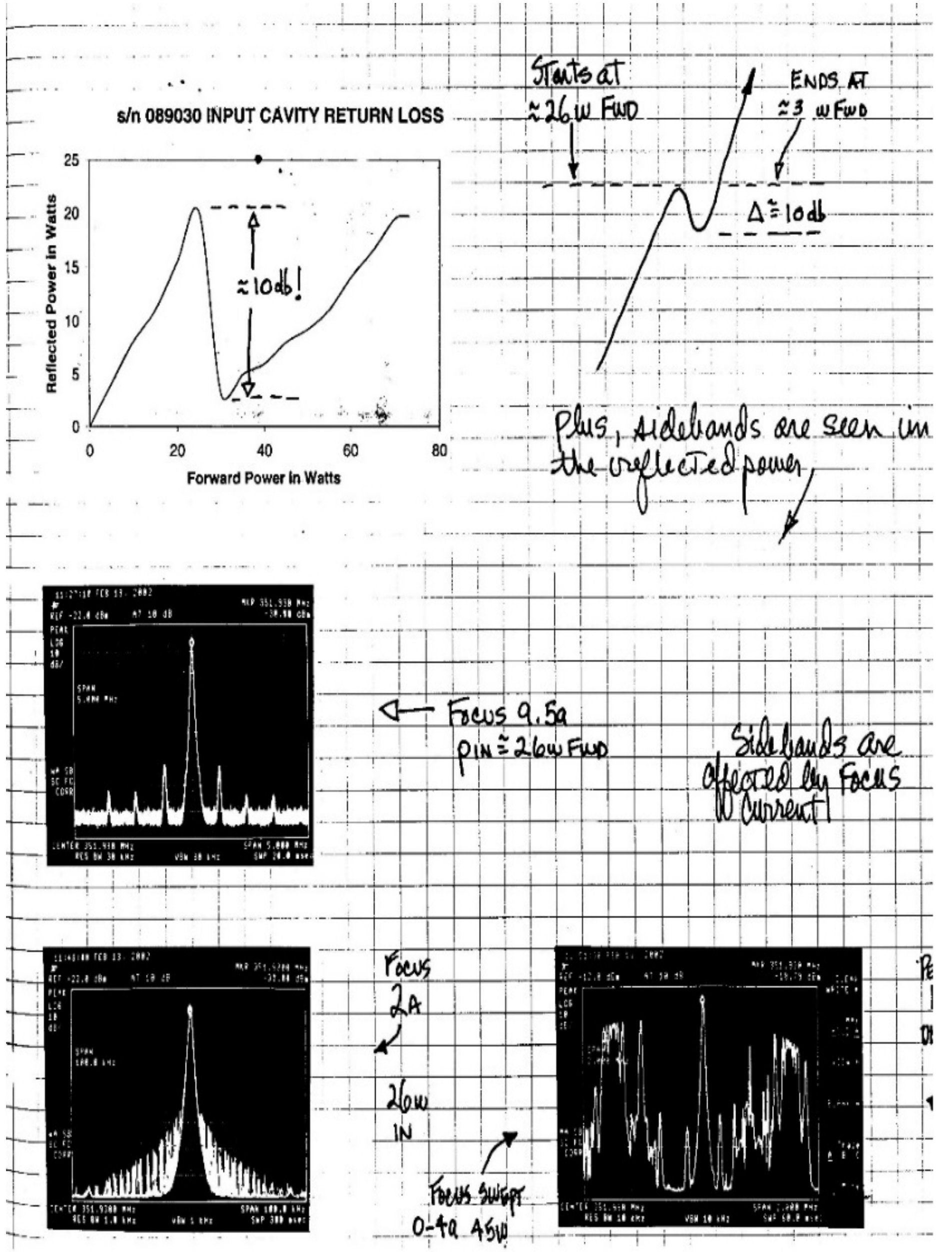
-- D. Bromberek

- The finished mill job
- Threaded holes were chased
- Vacuum is still intact
- The ceramic will be sandblasted, and the output waveguide transition re-assembled this July
- Klystron will be installed in the test stand and tested at full power in August



Longest Living 352-MHz Klystron at APS

- Thales TH2089A n. 089030
- Rebuilt in November 2000
- Installed in RF4 station in November 2005
- 84,730 filament hours as of June 13, 2018
- Only minor problems in 13 years of service:
  - → *Weak sideband instability at low power (≈100kW) -- input cavity multipactor suspected*
  - → *Minor water leak on body circuit due to leaking braze joint*
  - → *Cavity #3 pickup loop open – cannot read frequency*



Thank you for your attention!