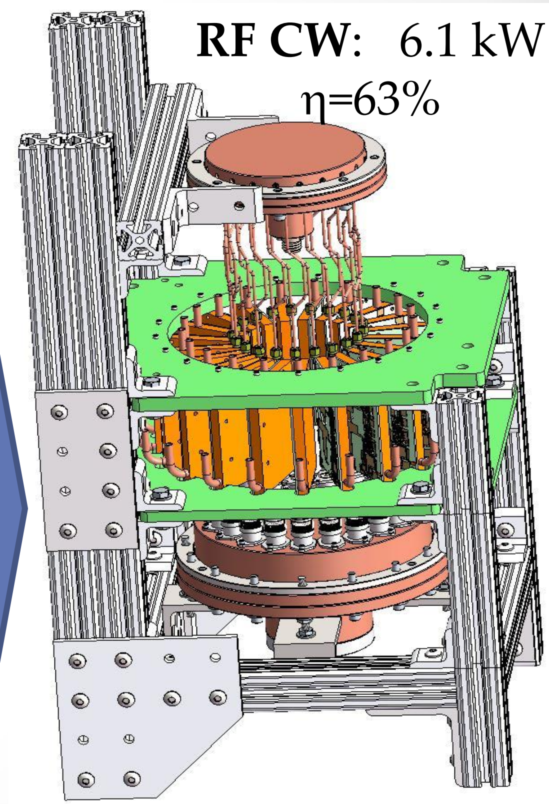
GaN Class F Power Amplifier for Klystron Replacement

Phase II completed ~02/10/2018

Principal investigator: Alexei V Smirnov

HV DC: 11.6 kV
RF CW: 8 kW, η≈33%

HV DC: 50 V
RF CW: 6.1 kW
η=63%

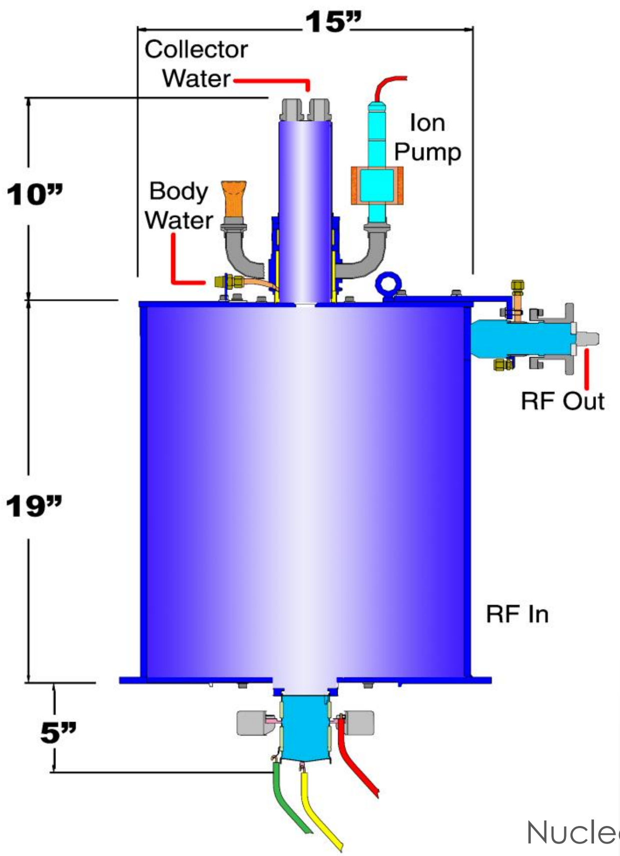


PM: Michelle Shinn

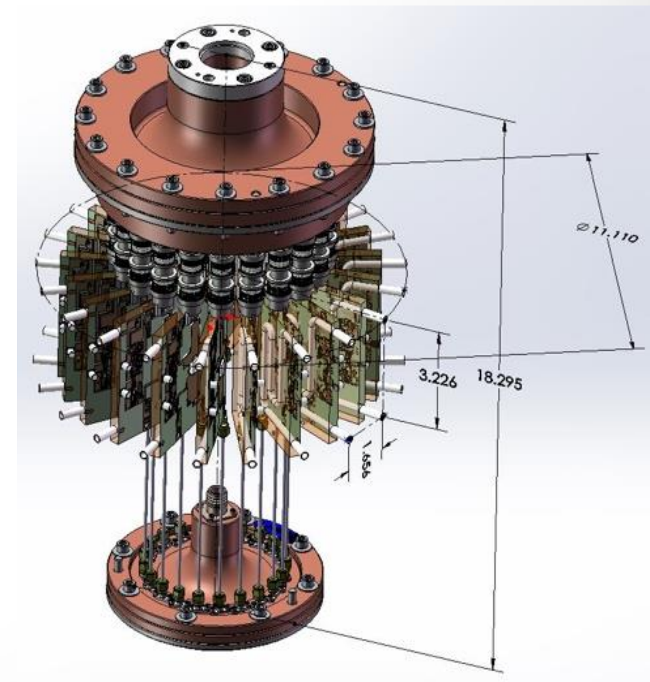
Topic 24b: NUCLEAR PHYSICS ACCELERATOR TECHNOLOGY (Radio Frequency Power Sources)

The GOAL

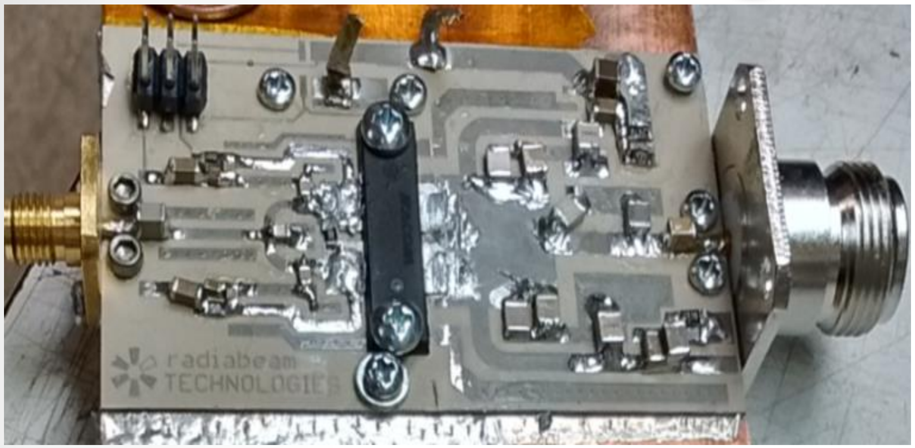
To develop a prototype and test a CW, all-solid-state, 1.497 GHz power amplifier specialized as space-compatible replacement of the VKL7811 klystron with ~16″×16″ footprint (and ~19″ height) at >60% efficiency and ~1.5-2 W drive power.



33% ⇒ >60% efficiency

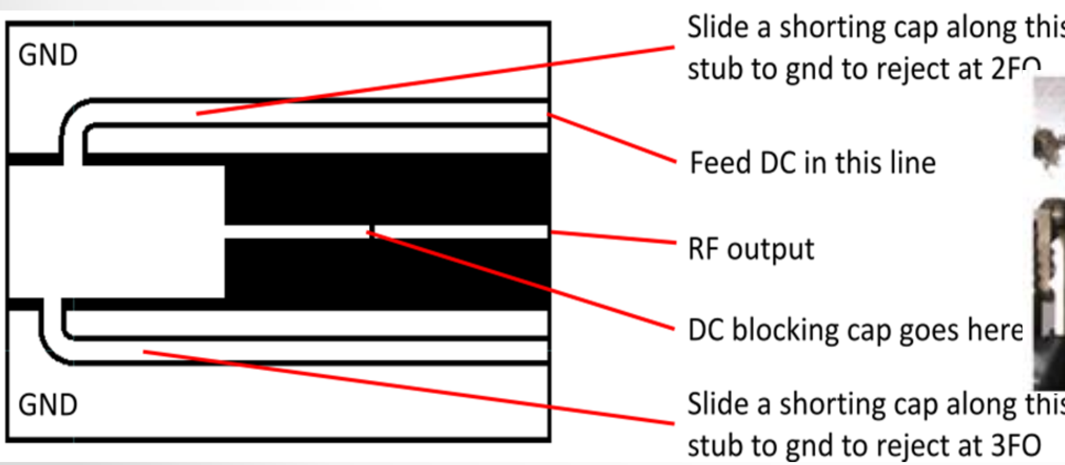


NPT2024 & Pallets: Testing & Tweaking



25 NPT2024 MACOM transistors were purchased and tested using different boards.

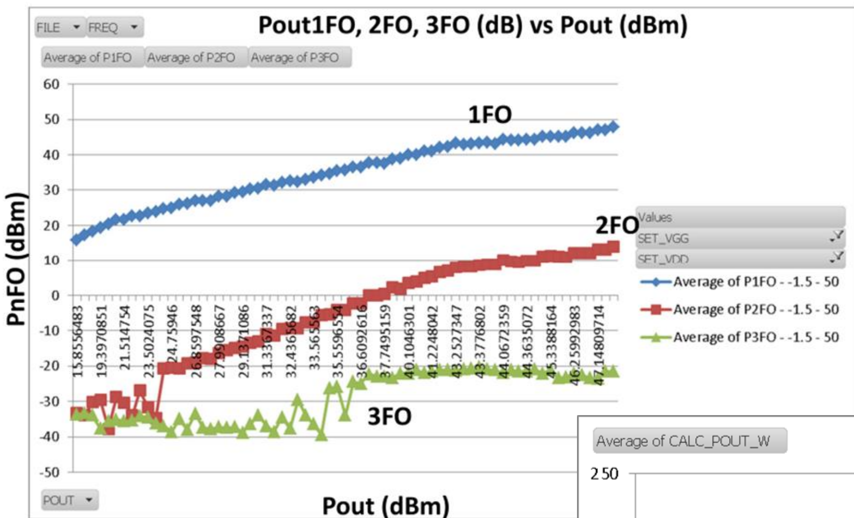
Tweaking method is developed to maximize efficiency and minimize harmonics



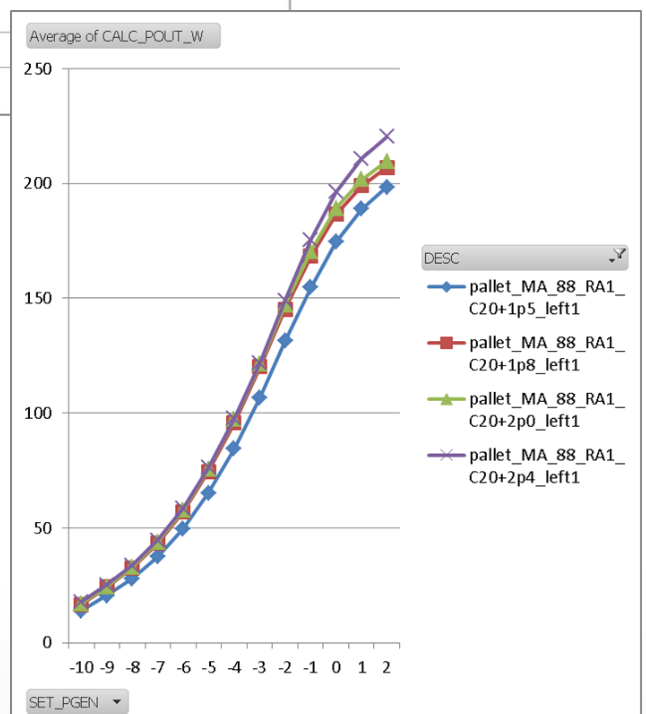
NPT2024 Pallet Tweaking

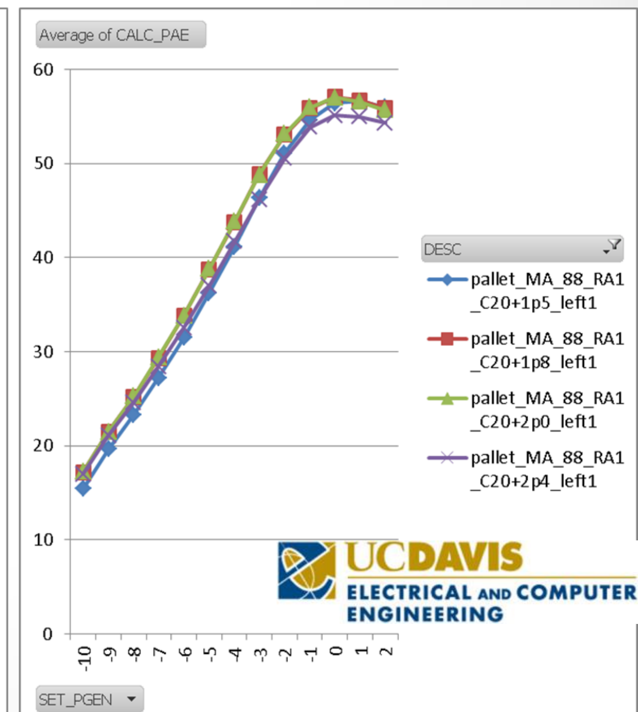
- NPT2024_88: VGG=-1.5V, VDD=50V
- Harm suppression average: P2fo < -30dBc, Pout3fo < -70dBc
- → A bit better than MACOM_TB especially 3FO

2nd harmonic is suppressed below -30 dB,
and 3rd harmonic below -70 dB



Power increase: ~10%
Efficiency: by ~3%





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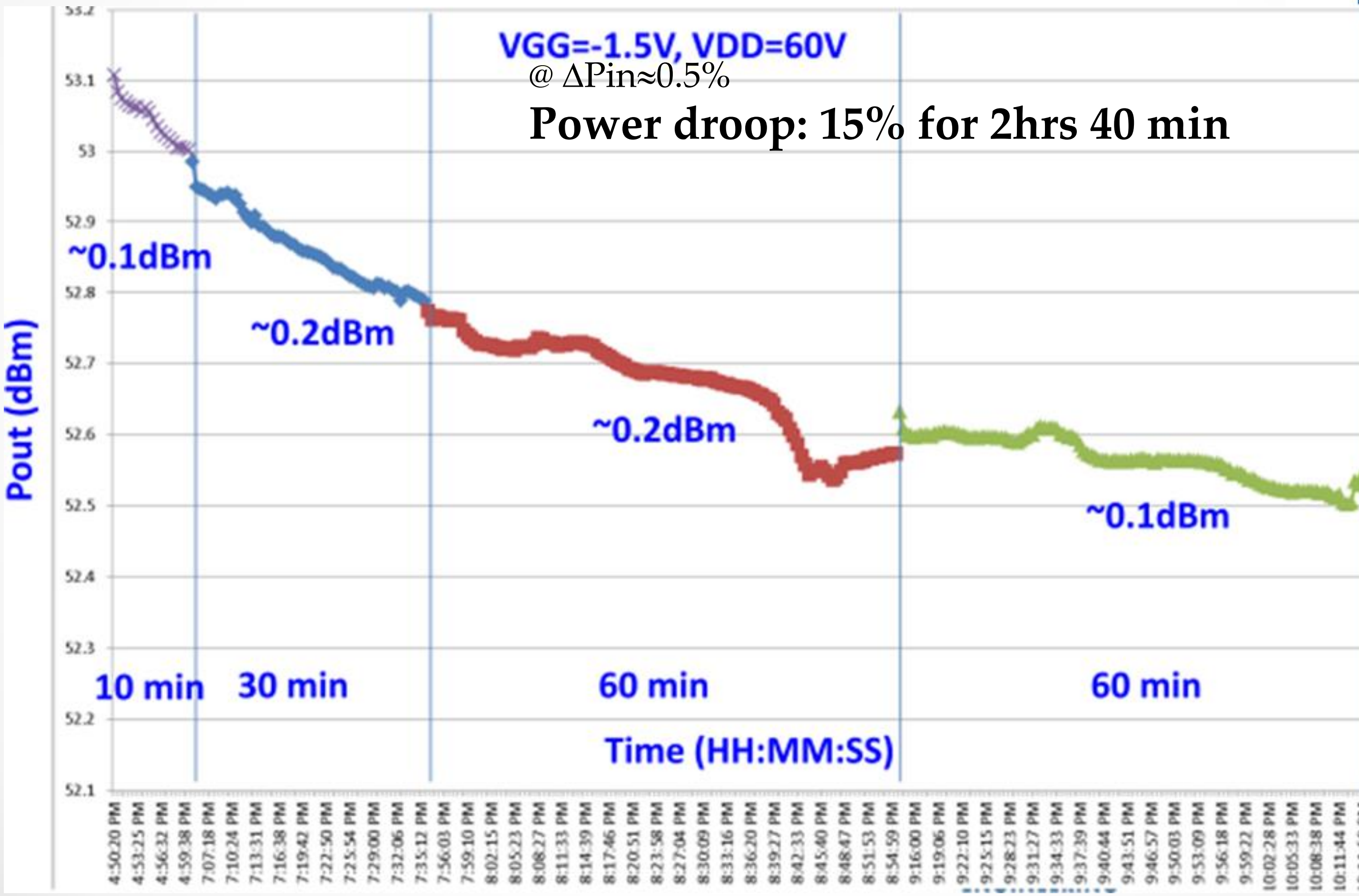
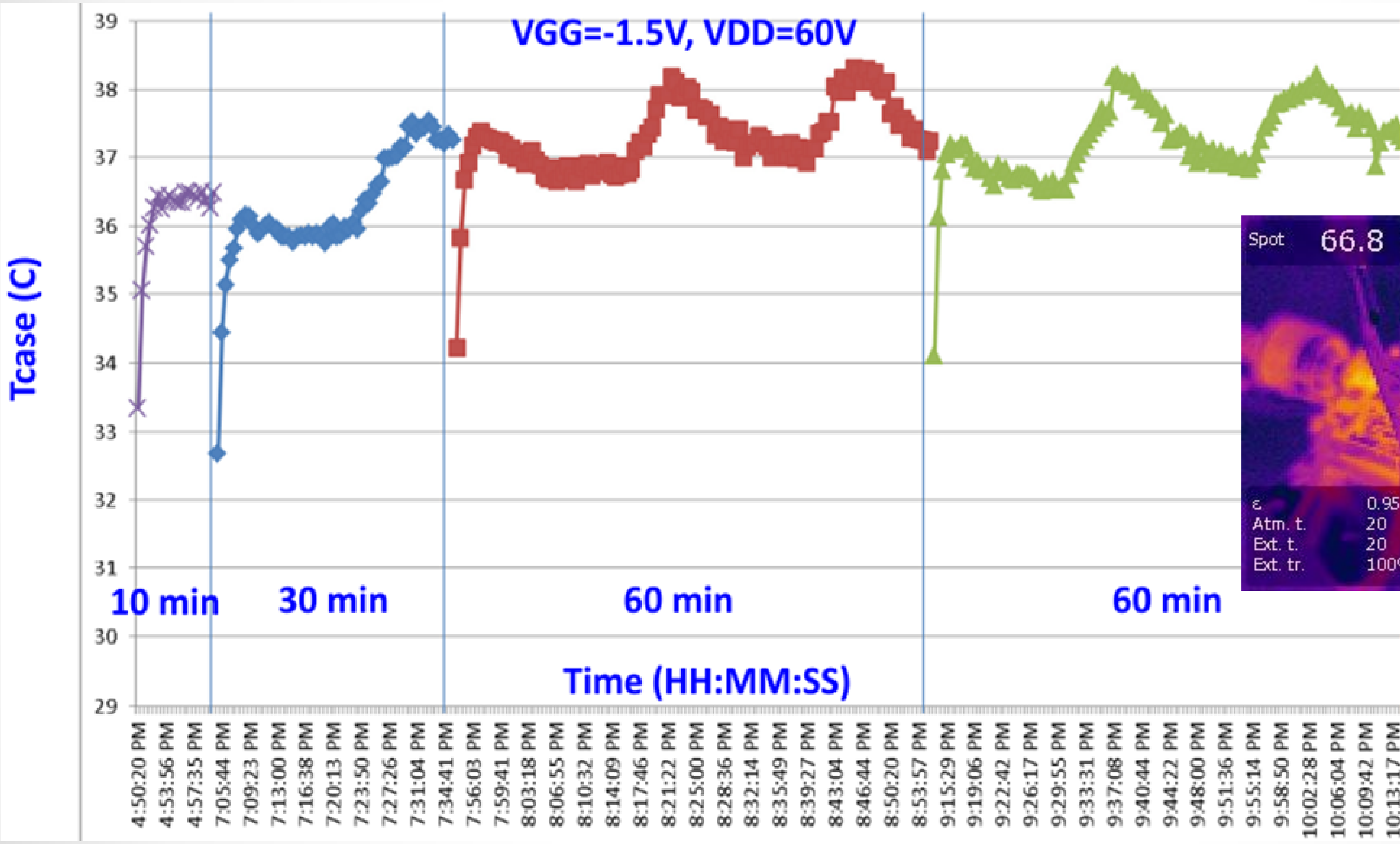
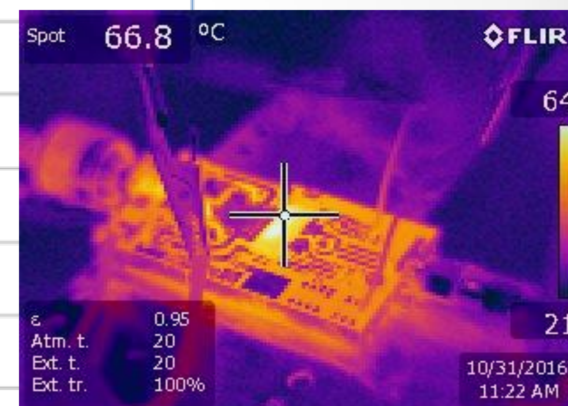
NPT2024: Power droop



Thermal instability





Conclusion on NPT2024

- Low power, gain and efficiency;
- Poor reproducibility and degradation;
- High failure rate (>25% failed);
- Performance spread (15% saturated power stdev)
- Thermal instability.

Available GaN power MOSFETS are not sufficient for the CW application

$\Rightarrow$ **Better CW power transistors are required.**

MicroSemi 65010GN

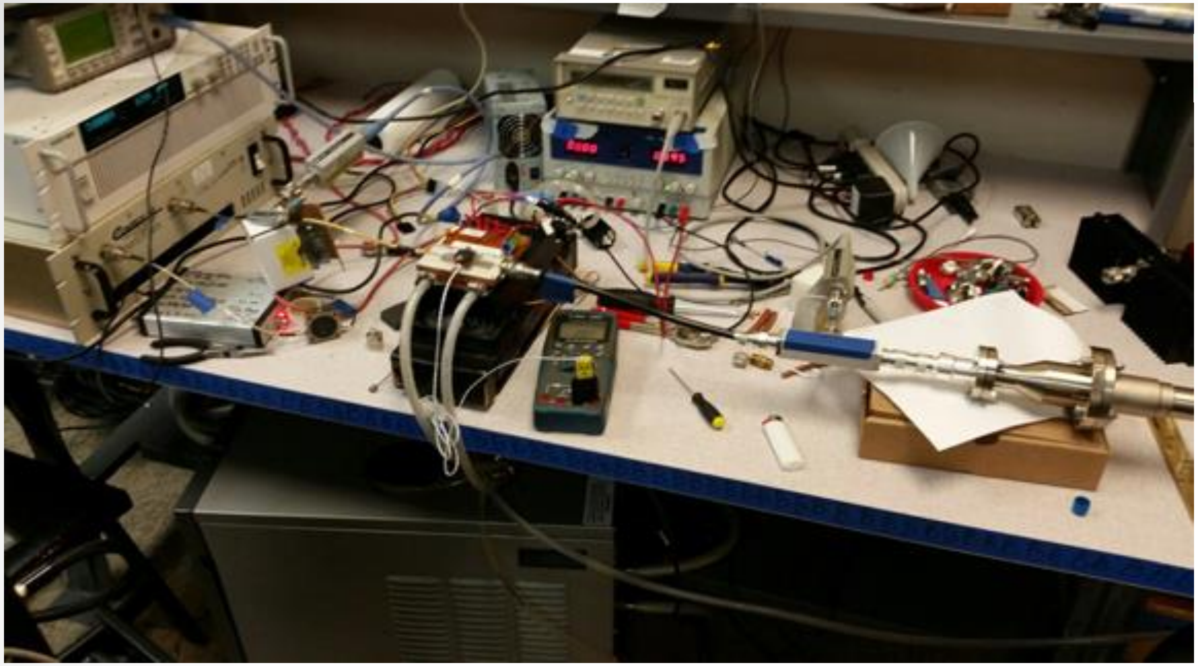
MOSFET design approach: integrated heat management, matching and power scalability

A novel GaN MOSFET has been developed specifically for this project:

- Very low thermal impedance (<0.35°C/W).
- High gain ~17dB .
- High power: ~300W at 52 V.
- >250 V breakdown voltage.
- >3 GHz cutoff frequency.
- Very low quiescent current.

Enables switching mode operation

65010GN Durability



Microsemi

No any degradation, power droop, or instability found for several days run!

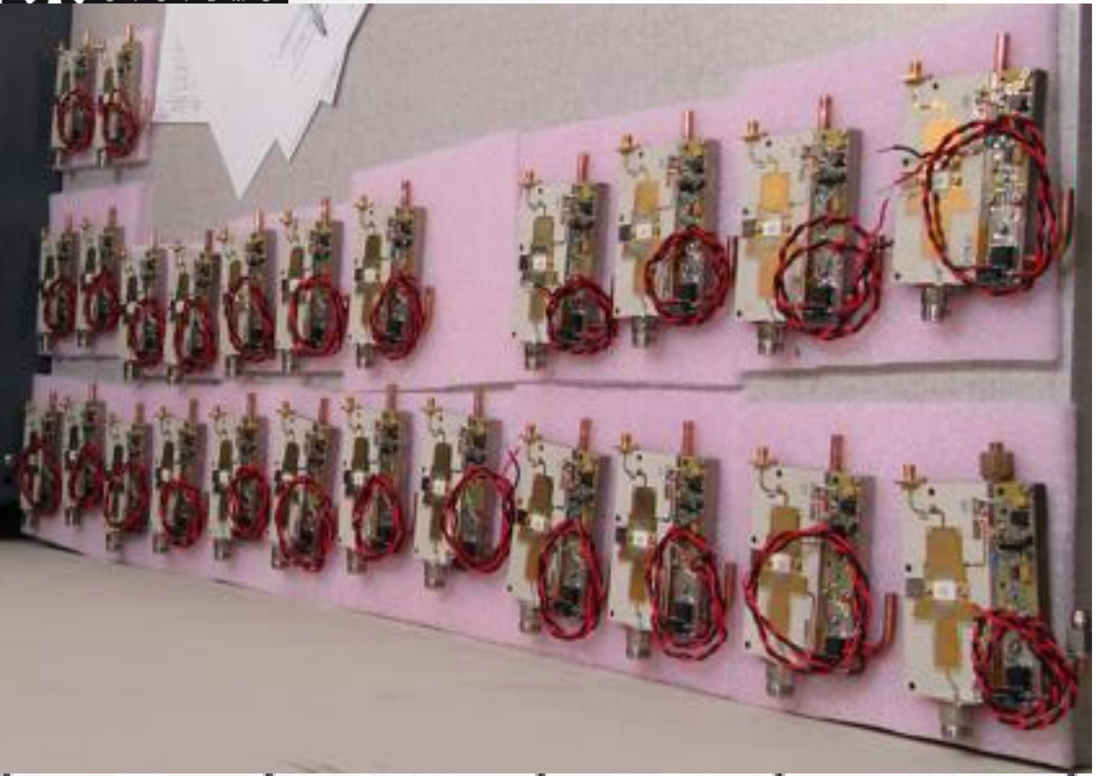
Measured at ~1.5GHz

Long run measurements of the 65010GN MicroSermi Demo Module

date	time	Input, W	PM_out, dBm	Output, W	Gain, dB	Id, A	Pd, W	T, thermocouple, C	T_chip, C
Sep 08	14:40	4.20	13.35	216.27	17.12	6.95	347.50	27.10	52.00
	15:10	4.15	13.25	211.35	17.07	6.90	345.00	27.10	52.00
	16:00	4.14	13.18	207.97	17.01	6.90	345.00	27.10	52.00
Sep 09	16:00	4.00	13.15	206.54	17.13	6.80	340.00	27.30	52.00
Sep 10	17:00	4.01	13.10	204.17	17.07	6.70	335.00	27.40	52.00
Sep 11	12:00	3.91	13.01	199.99	17.09	6.70	335.00	27.30	52.00

The best ever achieved long-run CW stability and durability without failures vs. other MOSFETS: NPT2024, CGHV14250, QPD1016.

26 × 65010GNA Pallets



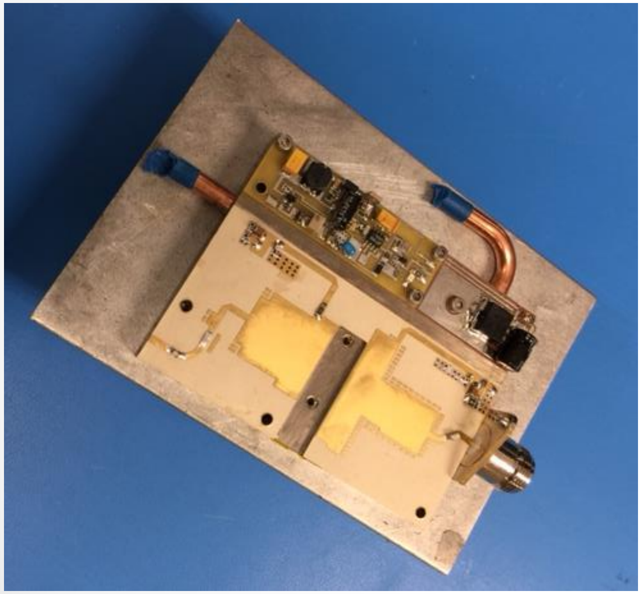
Relative pallet-to-pallet standard deviation is 6.4% for saturated power and 1.6% for the gain (dB).

Power St. deviataion	18.34349	0.27124535	Gain st dev.	Average eff.	63%
Averaged power	284.9	17.0	Av. Gain		

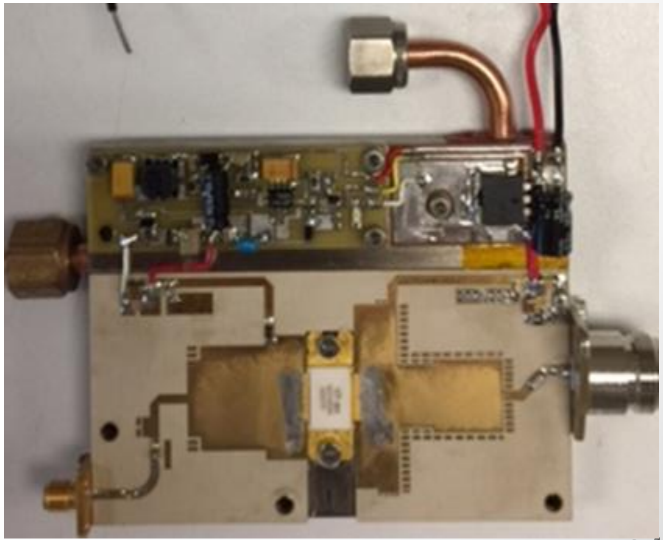
- Maximum power and drain efficiency: 309 W and 66%
- The lowest idle (at no RF) DC power consumption (**1.1% vs. >13%** for the best QPD1016 Qorvo transistor);
- High *power added efficiency* (PAE up to 64%);
- Highest saturated CW gain (17 dB vs. ~11 dB for QPD1016);
- Lowered source temperature (few degrees vs. QPD1016).

65010GNA Pallet Design

Pallet dimensions:
L=4″× W=3″
and Thickness = .250″



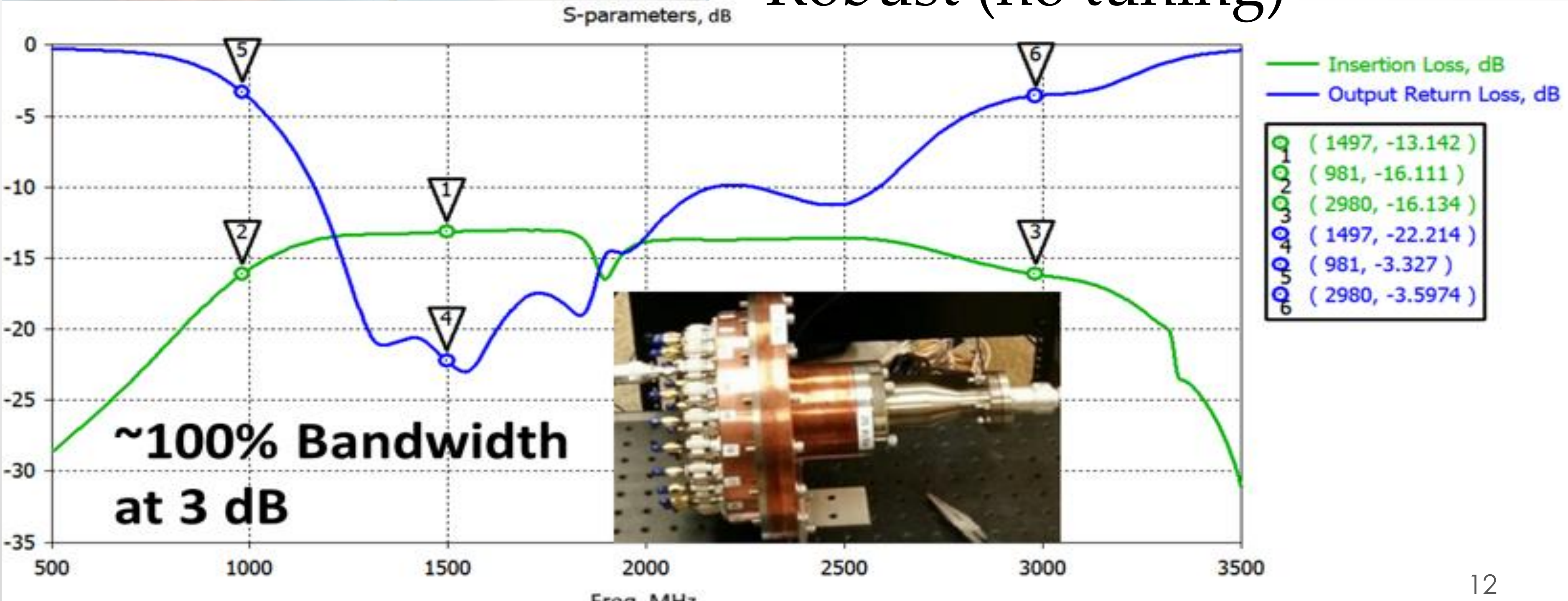
<u>Plug-and-play</u> power module:
no other bias or drain control/protection/driving circuitry is needed due to the IGBT heat management solution



Novel "wiggling" type combiner

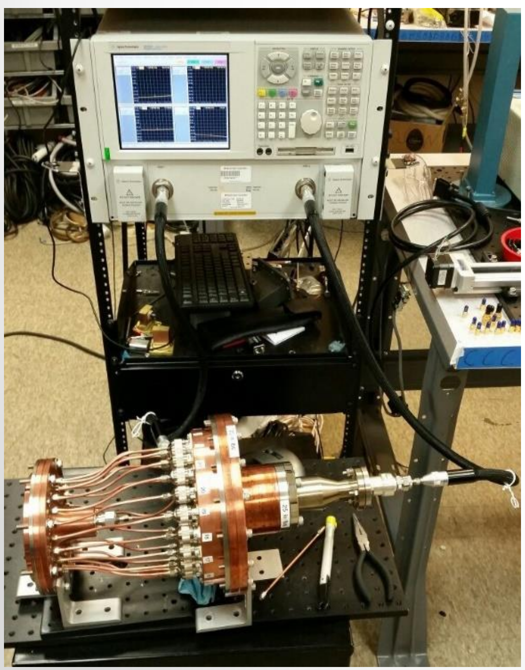
- Ultra-wideband
- Ultra-low loss
- High power
- Compact
- Robust (no tuning)

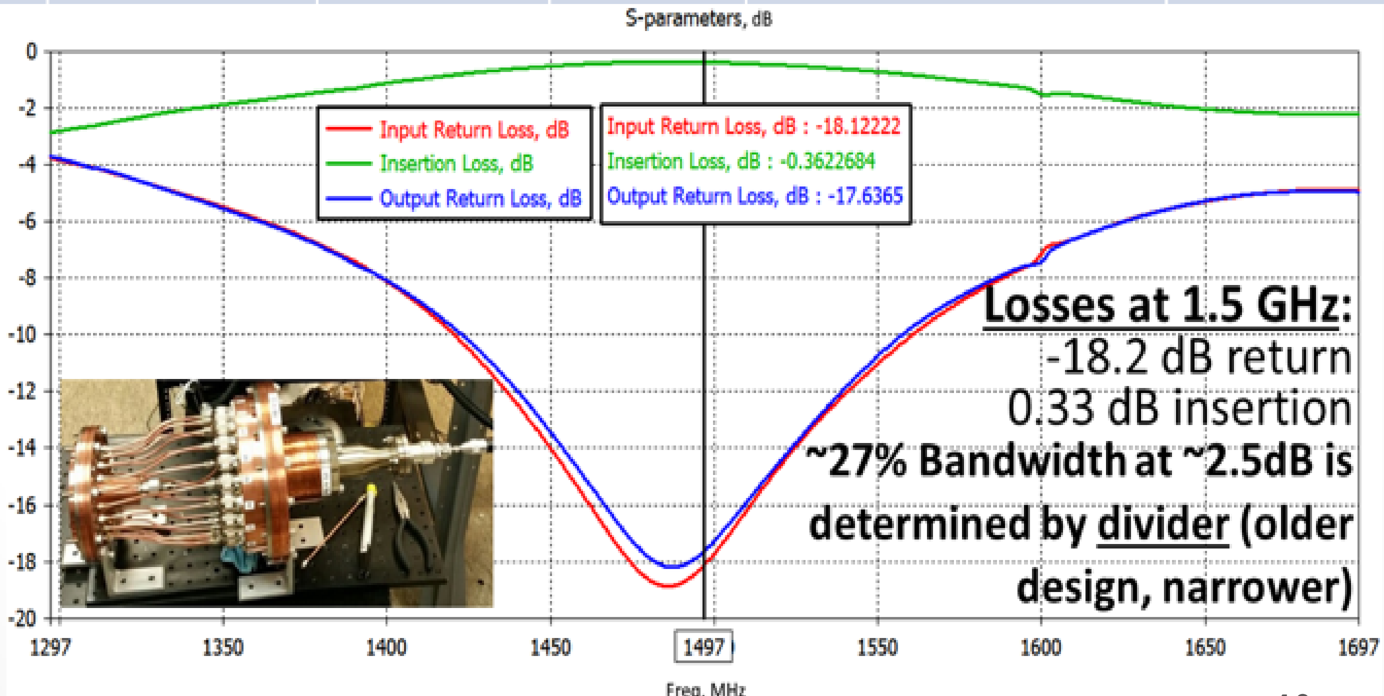
NIMA 870, 2017, p. 55



Combiner & Divider performance

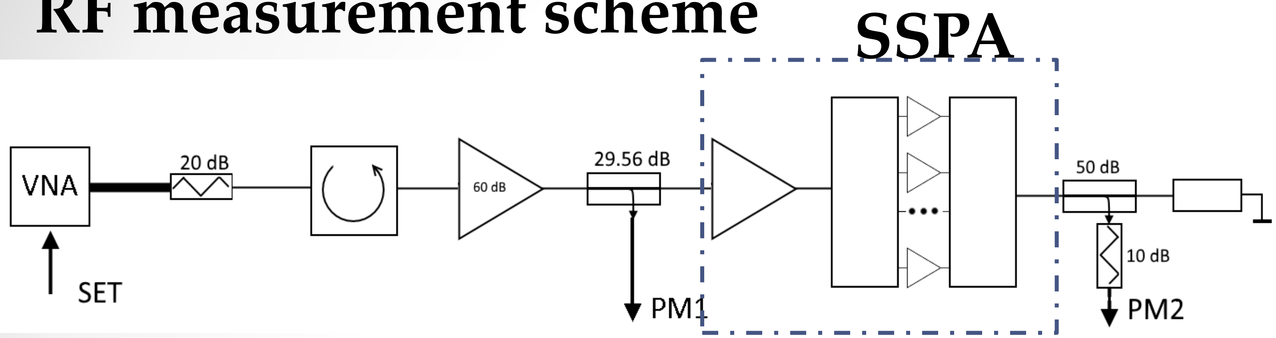
at ~1.5GHz	Insertion loss	Return loss	Isolation		Way-way rms inhomogeneity	
			Max	Min	Power	Phase
Divider	0.082 dB	-21 dB	26.8 dB	22.5 dB	1.5%	0.37°
Combiner	0.091 dB	-22.3 dB	24.9 dB	10.5 dB	1.45%	0.52°

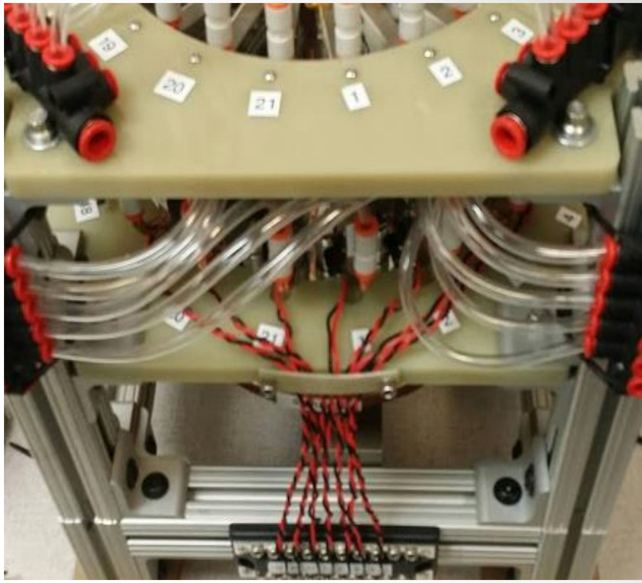




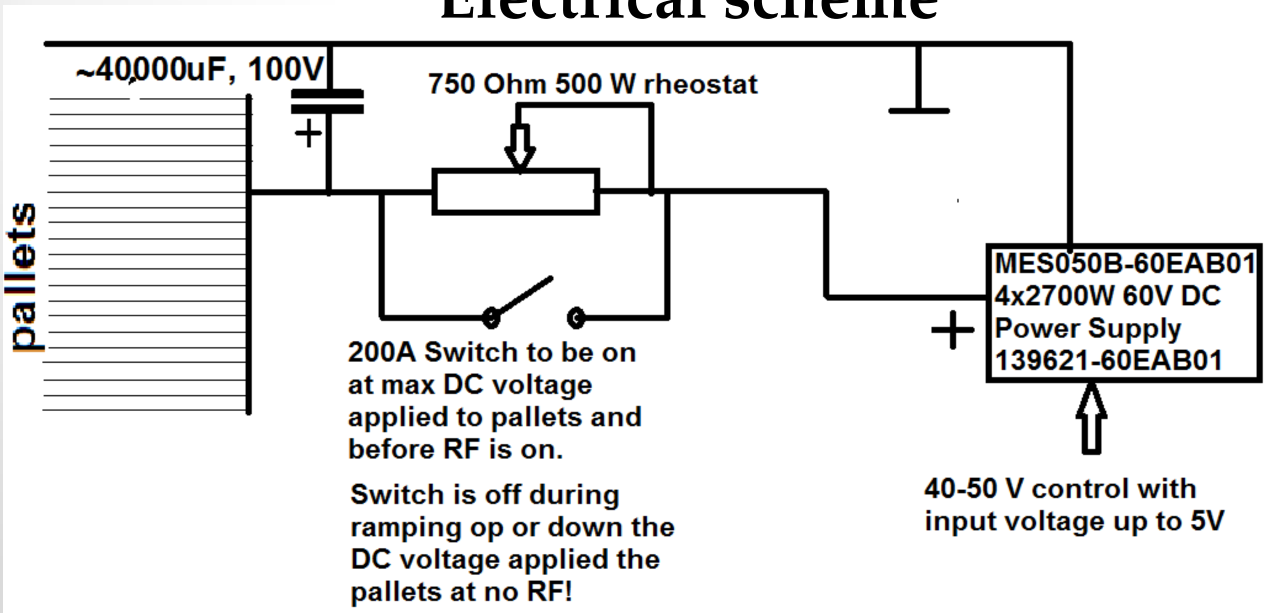
SSPA Assembly & Networks

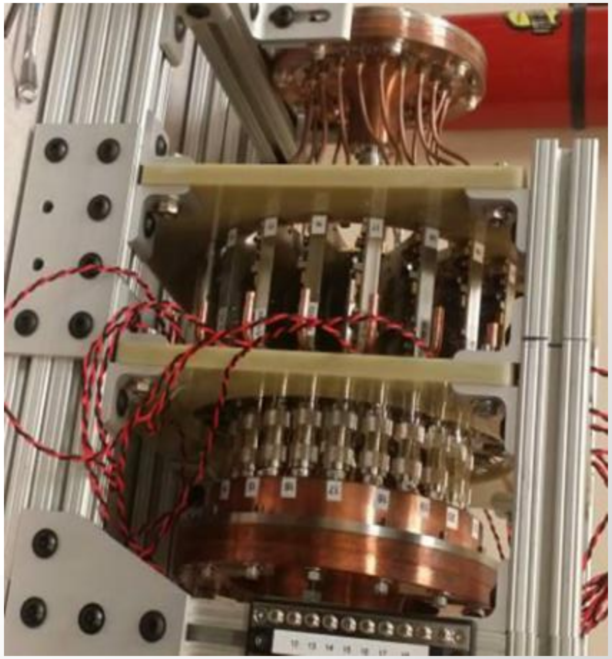
RF measurement scheme



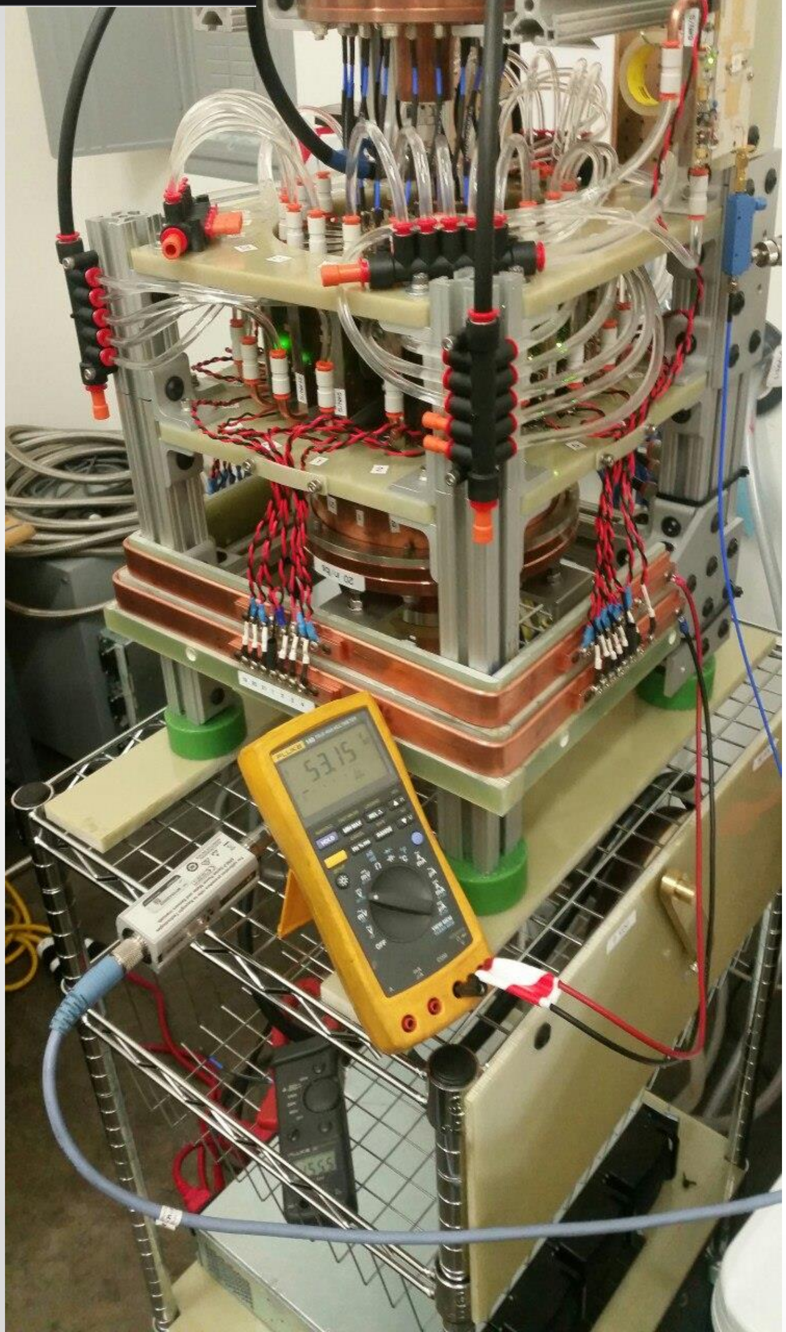


Electrical scheme

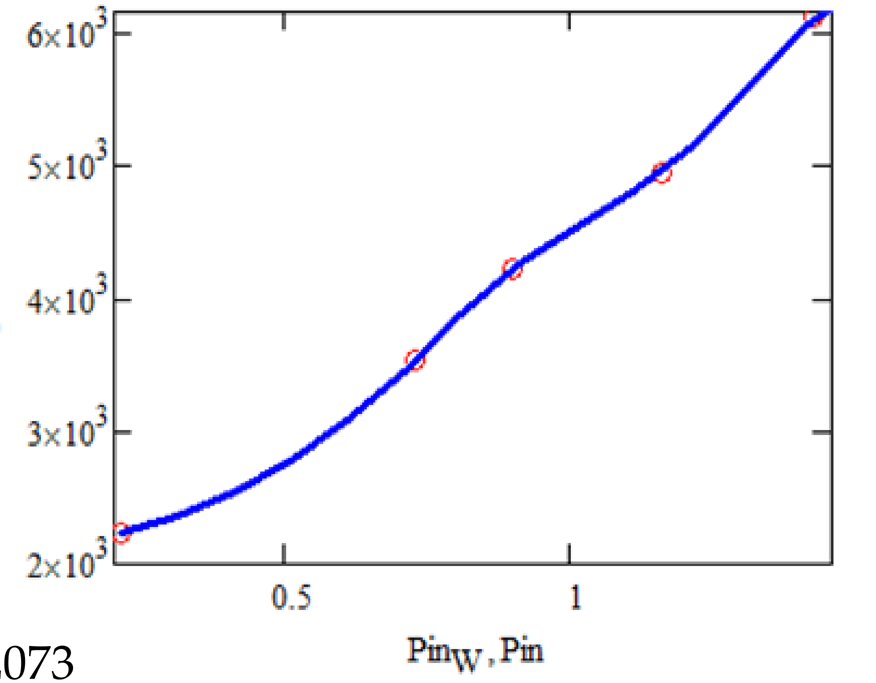




SSPA power



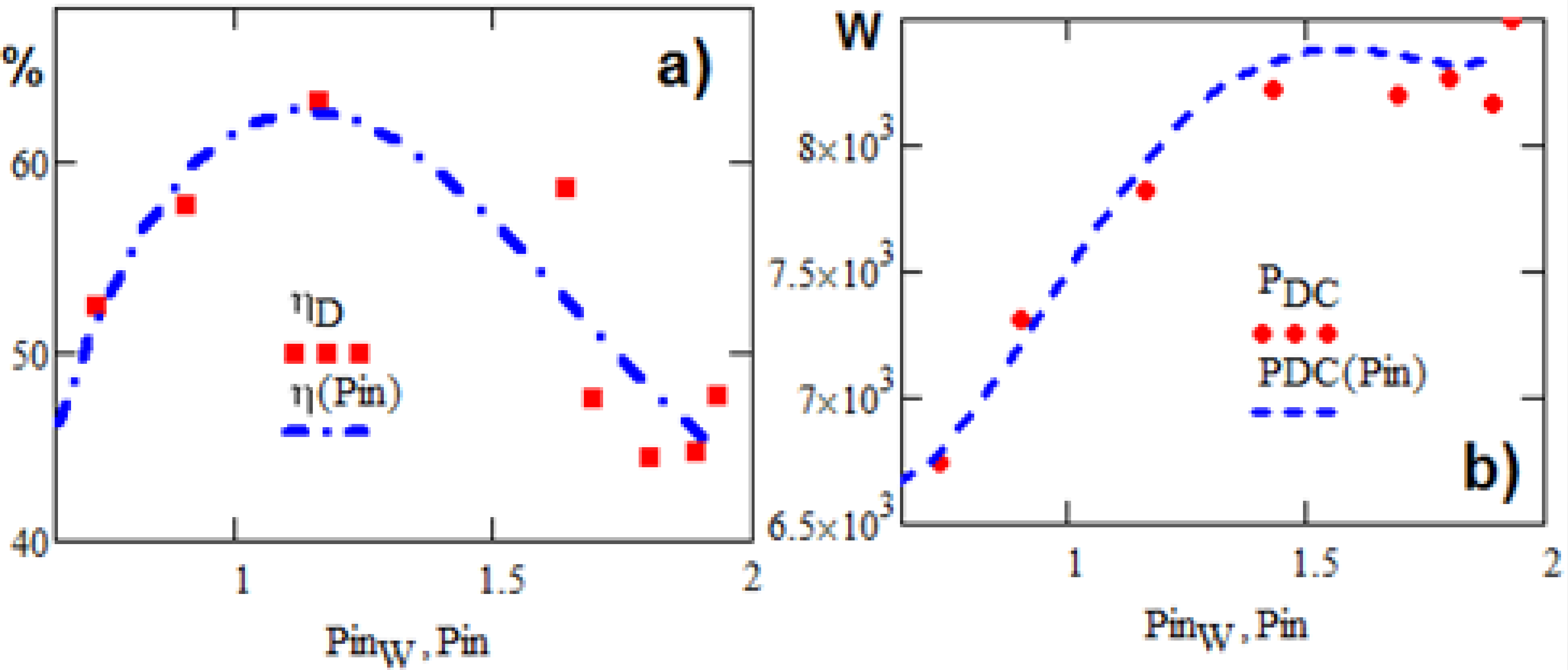
SSPA body dimensions: ~13.5″×14.5″ ×19″



THPAL073 in IPAC'18 Proceedings

Gain measured: 33-38 dB

Drain efficiency and DC power consumption



63% drain efficiency is achieved!

Project outlines

- The SSPA dimensions and gain fit well the klystron.
- The SSPA max efficiency exceeds almost twice that for klystron.
- The 3W/in^3 power density achieved at 100% duty exceeds much the CPI's VSS3605 SSPA (10% duty, η=35%)
- The quiescent SSPA current is only 0.84% of the full power current vs. ~100% for klystron.
- The novel 65010GNA pallets offer excellent capabilities for upgrade to enhance both power >370W and efficiency >70%.
- Almost perfect(as simulated) combiner-divider efficiency is measured at high power.

Market opportunities

- Jefferson Lab Electron-Ion Collider (JLEIC).
- Material processing and microwave chemistry.
- Radars and directed energy applications (defense).
- CW compact accelerators: UHF-L-band Rhodotrons (DHS).

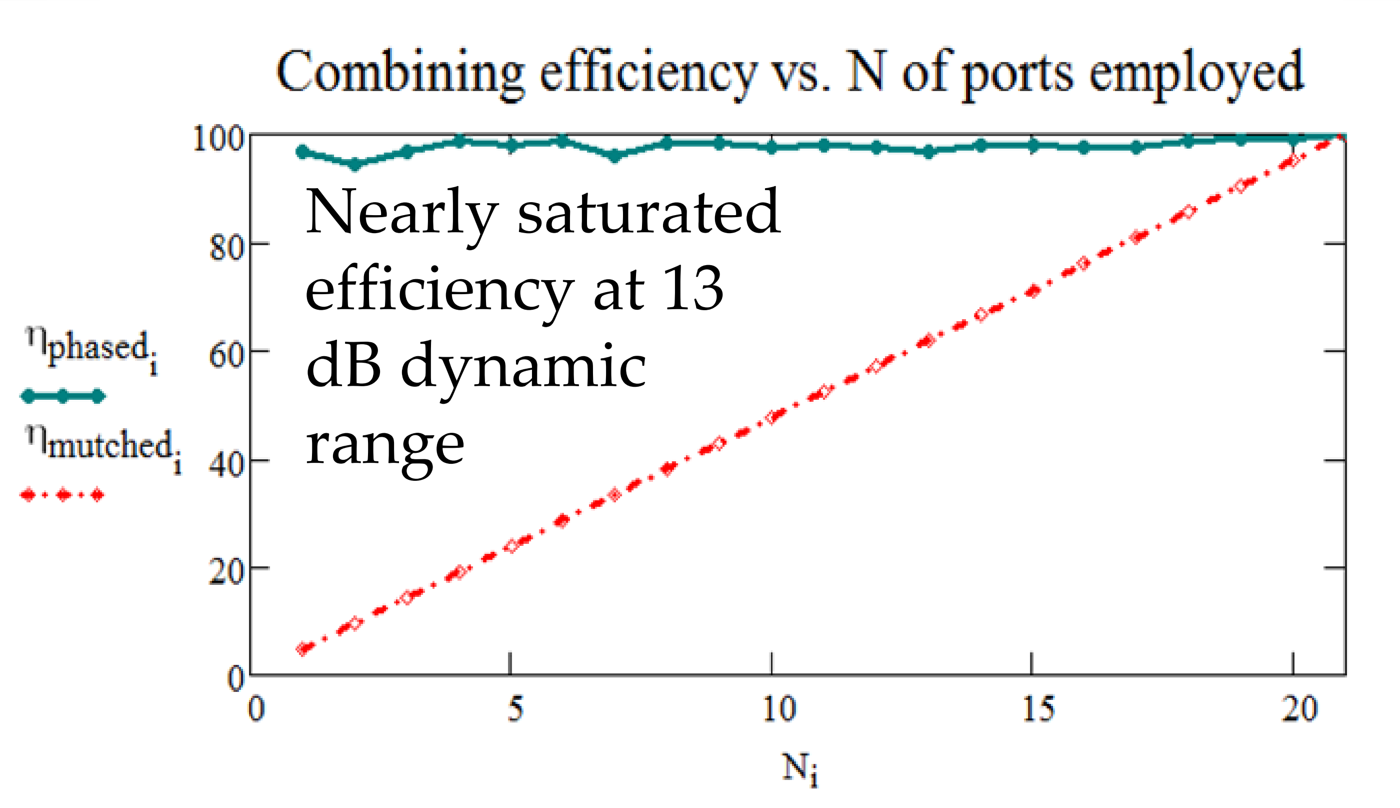
Interest expressed

- JLab
- CPI
- Navy
- Lambda Technologies
- RF components vendors (ANATECH)

Project outcomes

- 65010GNA to be modified to increase power and efficiency taking advantage of MicroSemi proprietary power-scalable technology enabling 275V breakdown $\Rightarrow$higher drain voltage ~120V.
- Need accommodation to Jlab environment: harmonics, water temperature, wide dynamic range of power, phase stability.
- Develop broadband version of the SSPA for commercial applications (to include 1.3 GHz).
- Novel opportunity for efficiency enhancement in wide dynamic range.

Novel opportunity for efficiency enhancement in wide dynamic range



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