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# *Solid State RF Amplifier Development for 805 MHz Klyston Replacement at LANSCE*

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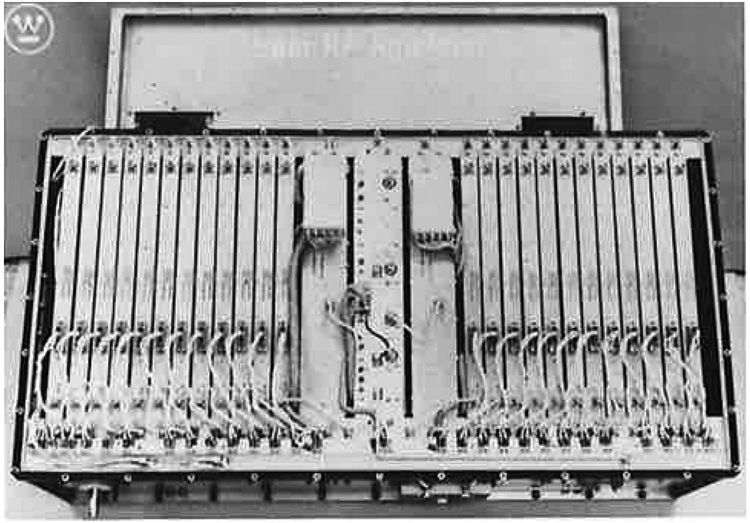
# Forty-four Klystrons used for 805 MHz RF power for LANSCE Coupled-Cavity Linac

- 1.25 MWp, 150 kW average power, 1960s mod anode design
- Concerns of long term supply past 2050
- Beam HV systems obsolete
- 50+ year old technology is difficult to staff with early career engineers and technologists without lengthy training period (years)

# In 1980s, LANL Collaborated with Industry on 2 x 60 kW SSA for Space Accelerator BEAR

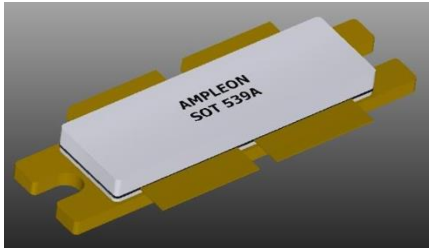
2.5 kW module using
10 x 500 Watt BJT



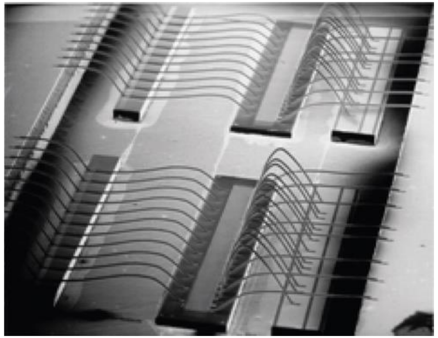
60 kW PA, 36 x 18 x 10 inches, 120 lbs

Launched July 1989 from White Sands Range

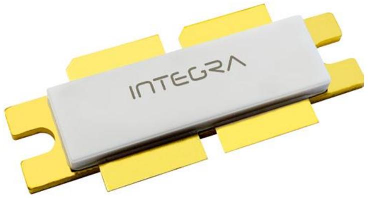
# RF Power Transistors – Silicon LDMOS is Leader




- Below 400 MHz LDMOS ~1.8 kW $P_{sat}$
- Large transistor dies used for higher power have higher drain to source capacitance, reduced gain and efficiency, very low matching impedance
- 805 MHz power < 1 kW per transistor

# Gallium Nitride on Silicon Carbide High Electron Mobility Transistor





- Smaller structure with lower capacitance and highest power density
- Capable of higher temperature operation, up to 225 deg C internally
- Now able to generate 6-7 kW depending on voltage, up to L Band for avionics

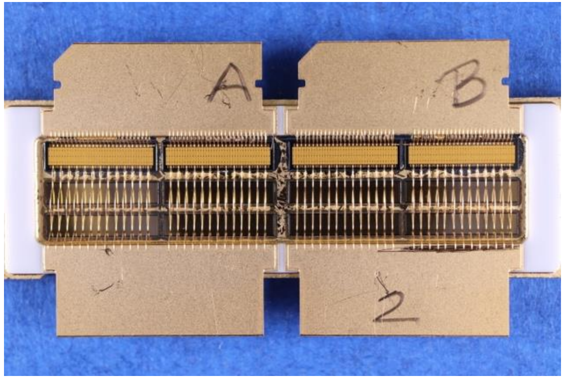
# Gallium has 3 Valence Electrons, Nitrogen and Arsenic have 5

| Material | GaN | Si | GaAs | SiC (4H) |
|---|---|---|---|---|
| Bandgap (eV) | 3.4 | 1.1 | 1.4 | 3.2 |
| Breakdown Field Strength (MV/cm) | 2 | 0.3 | 0.4 | 2.2 |
| Saturated Velocity (x10^7 cm/s) | 2.5 | 1 | 1.5 | 2 |
| Thermal Conductivity (W/cm-K) | 1.5 | 1.3 | 0.4 | 4 |

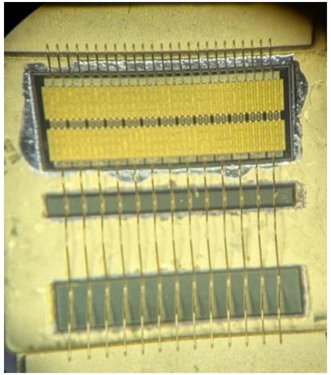
# Our SSA is using GaN on SiC Transistor Technology

- 805 MHz with LDMOS required excessive devices (system must fit in Klystron space)
- Integra Technologies released HV GaN in 2022; long device production life is forecasted
- Navy is investing in very high power and bandwidth also
- They don’t sell in the wireless market, so their production runs are smaller
- Collaborating with combiner company (Werlatone) for the blade design and overall combining architecture
- Third year of internal R&D, progress shown in following slides

# IGN815 is Gen 3 HEMT




IGN815, 3.6 kWp, 12% duty Factor



IGN825, First die is mounted, ¼ of 5 kWp, 12% duty Factor

- Made from four inch GaN on SiC wafers from foundries
- 4 x 0.25” wide transistor dies, each having 78 x 1 $\mu$m gate length, stable design
- 78 mm gate periphery per die for 3.6 kWp, 117 mm for 5 kWp part
- Ag bond wires, AuSn soldered die attach to CPC flange

# IGN815 Preliminary Datasheet

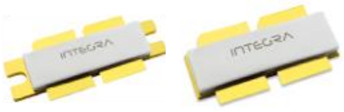
**IGN815** | RF Power Transistor
**IGN815S**

INTEGRA
RF POWER DEVICES

## UHF-Band, GaN/SiC, RF Power Transistor

**805 MHz | 3600W | 75% Efficiency typ | 20 dB Gain typ | 100 V | 1ms Pulse Length, 12% Duty Cycle**

IGN815 and IGN815S are high power GaN-on-SiC RF power transistors that have been designed to suit the unique needs of particle accelerator systems. They supply a minimum of 3600W of peak output power, with typically 20 dB of associated gain and 75 % efficiency. They operate from a 100V supply voltage. For optimal thermal efficiency, the transistors are housed in a metal-based package with an epoxy-sealed ceramic lid.



### FEATURES

- GaN on SiC HEMT Technology
- Output Power >3600W
- Pre-matched Input Impedance
- High Efficiency - 75% typical
- 100% RF Tested under 1ms, 12% duty cycle pulse conditions
- RoHS and REACH Compliant

### APPLICATIONS

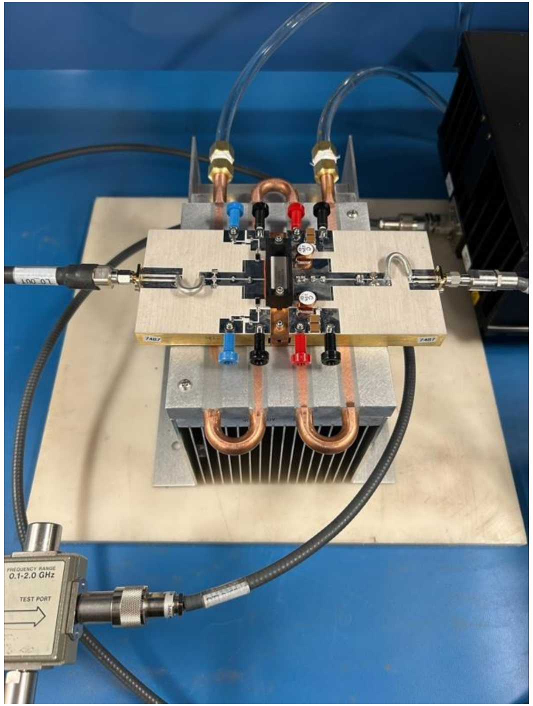
- Particle Accelerator Systems

**Table 1. RF Electrical Characteristics (Case temperature = 30 °C unless otherwise stated)**

| Parameter | Symbol | Min | Typ | Max | Units | Test Conditions |
|---|---|---|---|---|---|---|
| Gain | G | 16 | 20 | 24 | dB | $P_{OUT}$ = 3600W<br>f = 805 MHz<br>1ms pulse length, 12% duty cycle<br>$V_{DS}$ = 100V, $I_{DS}$ = 75mA per side |
| Drain Efficiency | η | 65 | 75 | 85 | % | |
| Pulse Droop | D | 0 | -0.65 | -0.8 | dB | |
| Input Return Loss | IRL | 7 | 15 | 18 | dB | |
| VSWR Mismatch Stability | VSWR-S | 2:1 | | | | |
| VSWR Withstand | VSWR-LMT | 5:1 | | | | |

Note: Consult Integra Technologies Application Note 001 for information on how RF output power and pulse droop are measured.

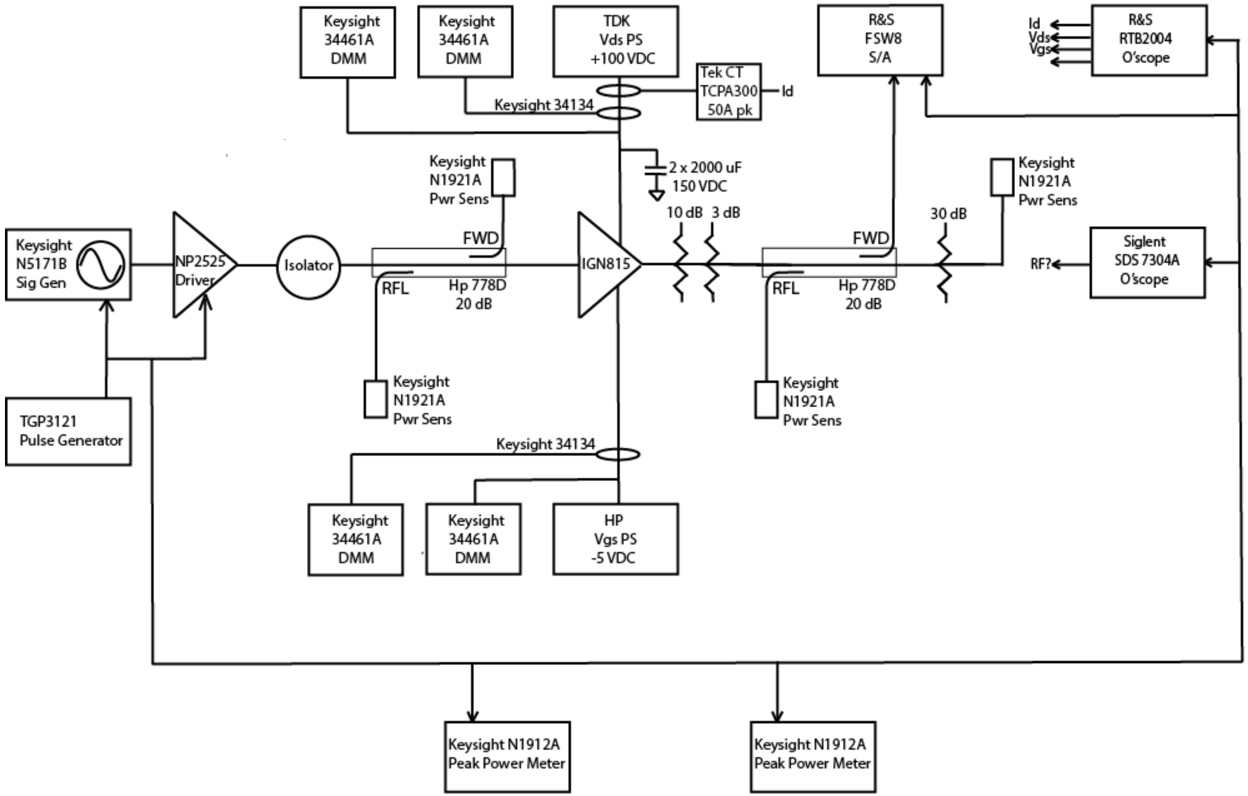
# Push-Pull Test Pallet




**3.6 kWp, 12% DF, 100 Volt Vds**

**185 deg C channel temp measured at factory**

# LANL Test Bench Diagram



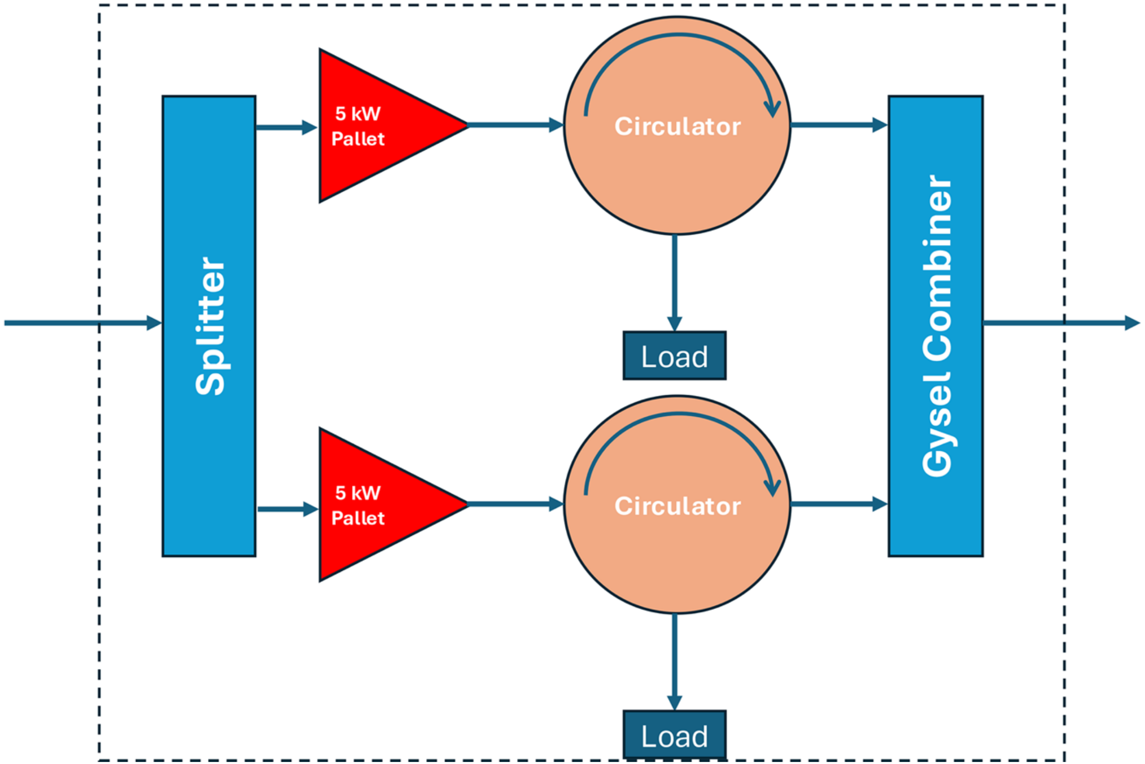
# 5 kWp 117 mm Periphery Chips are in Test at Fab

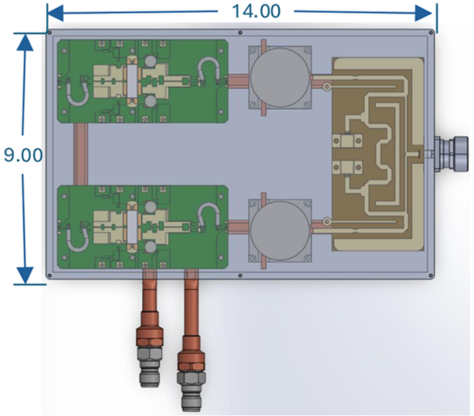
- Transistor chip development is ~ ¼ cost of tube NRE
- Pizza mask from wafer lots, testing design variations
- Final chip selected, RF and thermal testing
- Packaged transistor development
- Tuning, measurement of RF parameters
- Final RF test fixture developed
- Pallet design and evaluation - first item test
- Takes about 1 year

# Combining Power Modules to get 1.25 MWp

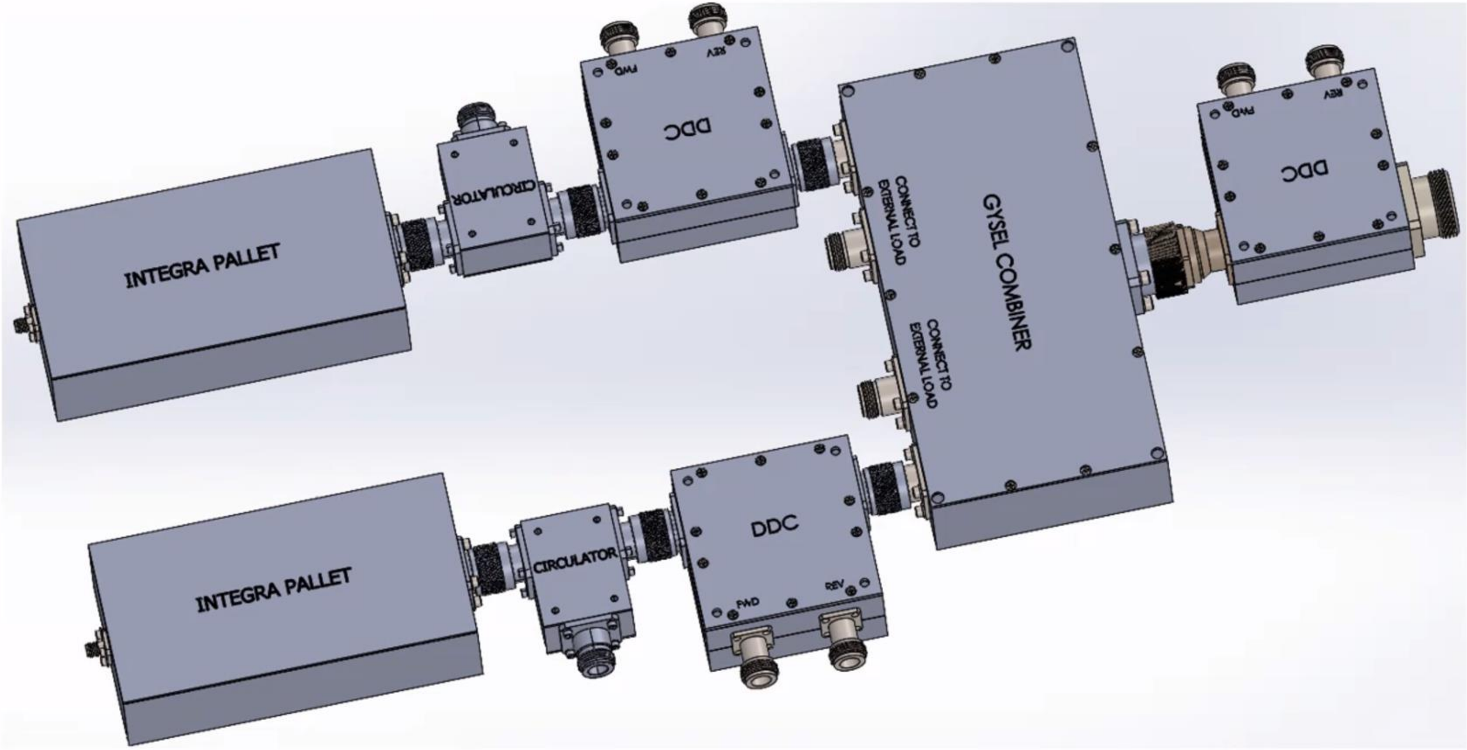
***"The rest of the story…"***

# 10 kWp Maximum for Blade due to Output Connector

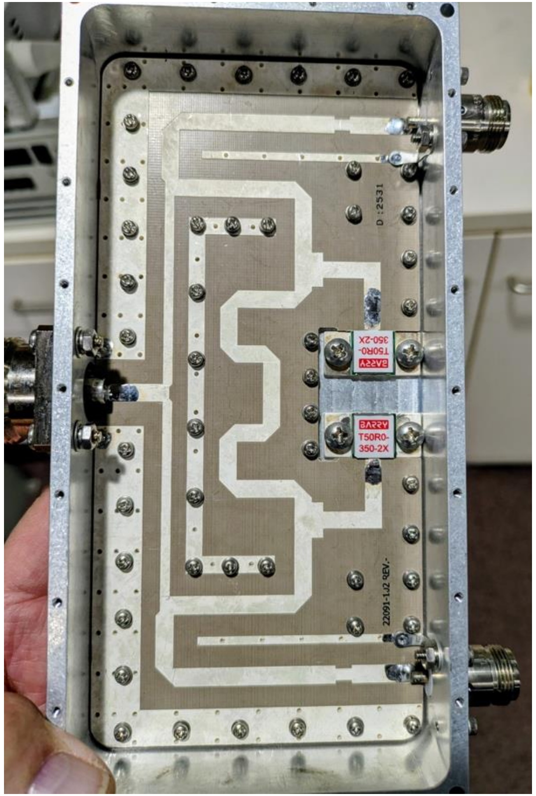


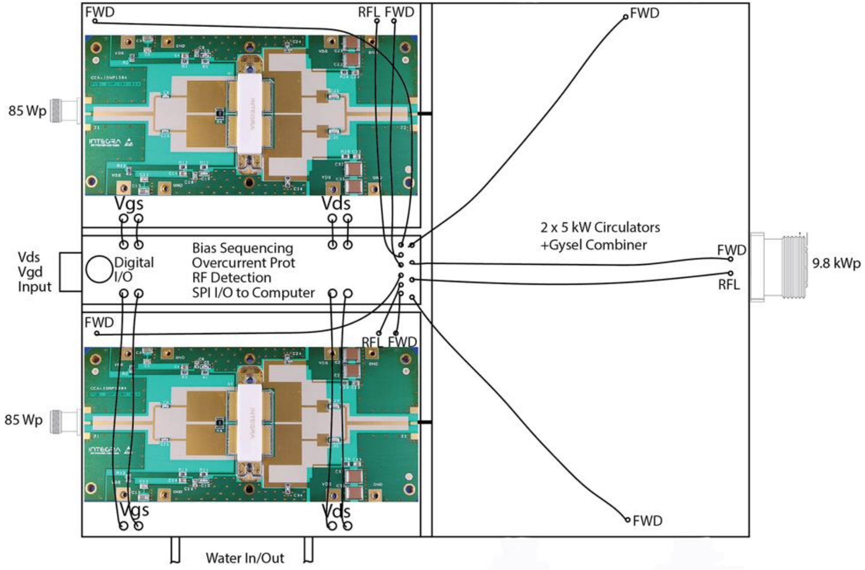
# Benchtop Prototype of Components in Blade

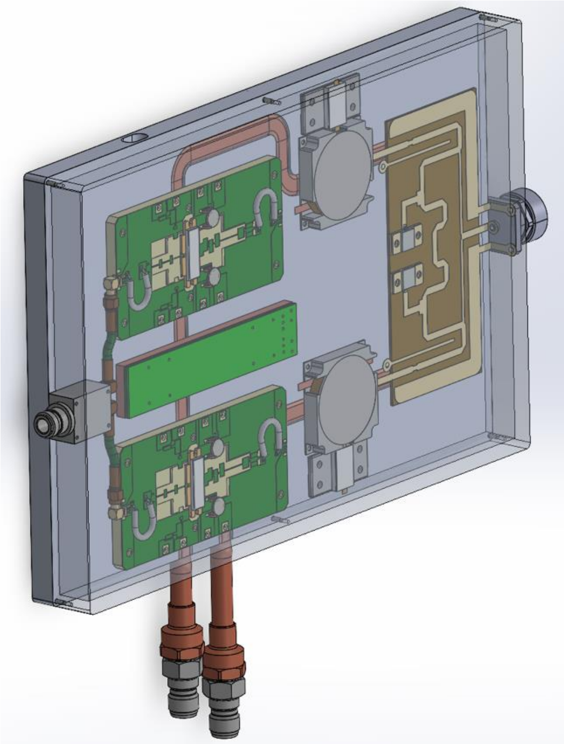


# 2-Way Isolated Gysel Combiner

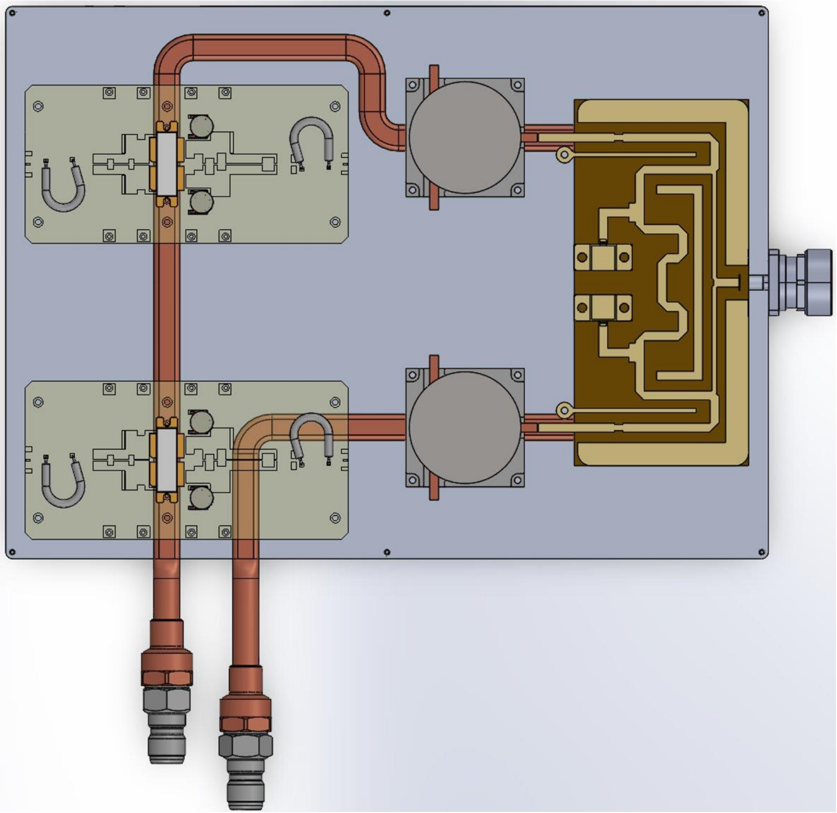


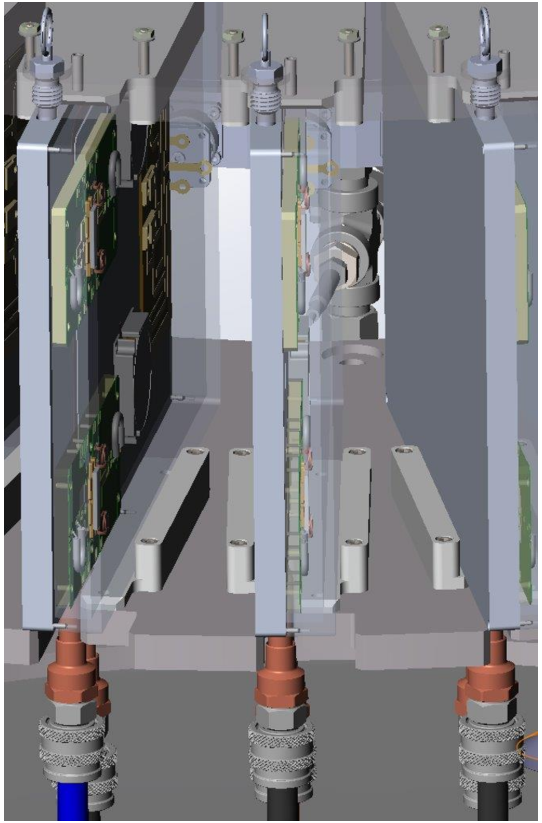
# Blade Details



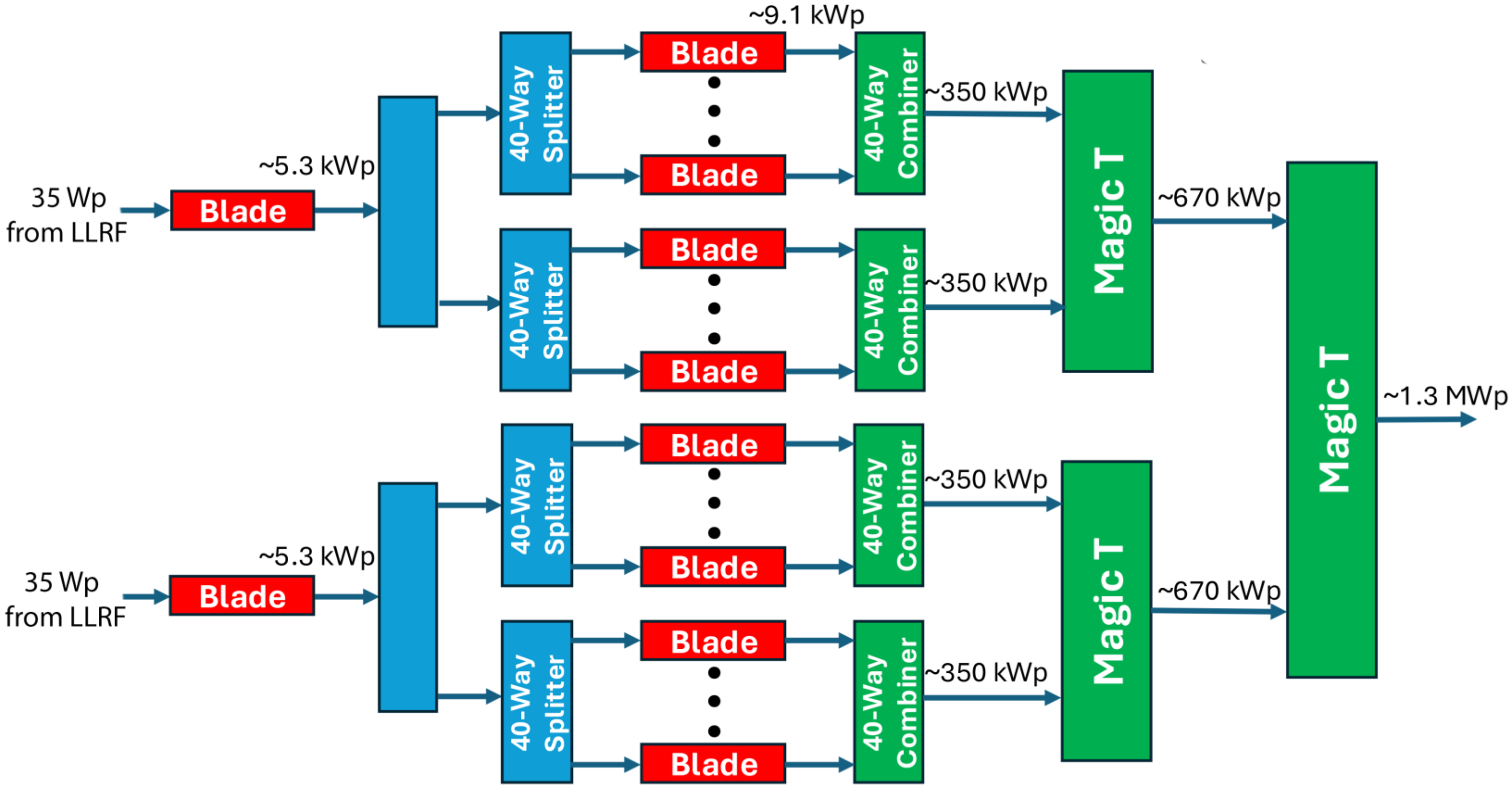



# Blade Cooling Details

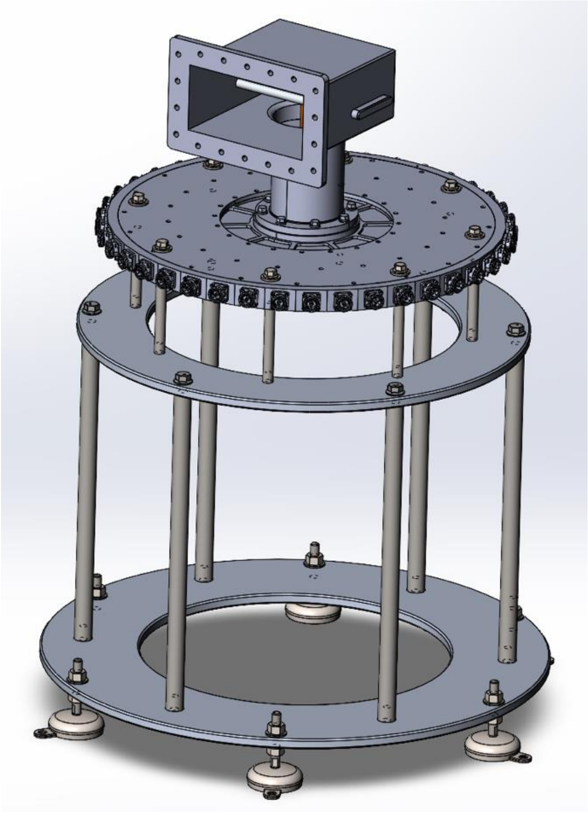




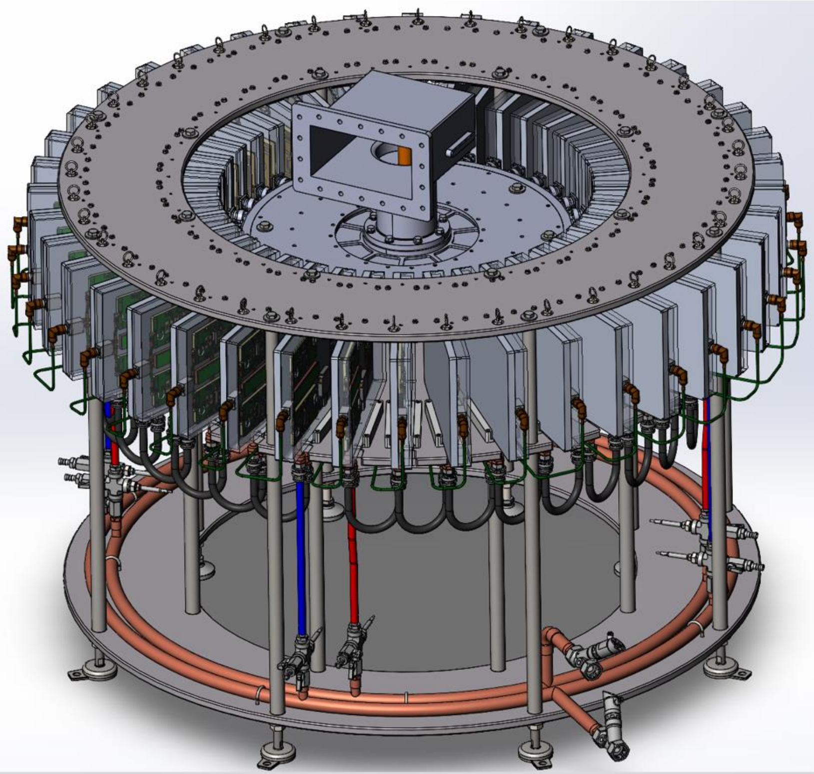
# Overall Power Amplifier RF Power Flow

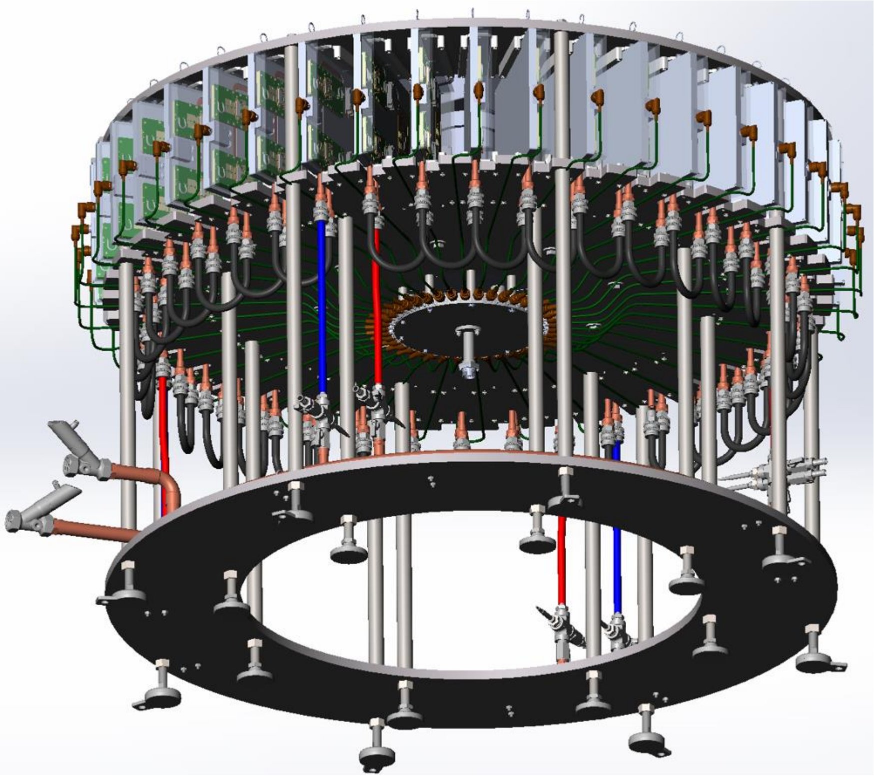


# 40-Way Radial Power Combiner



# ¼ Power ~ 350 kWp





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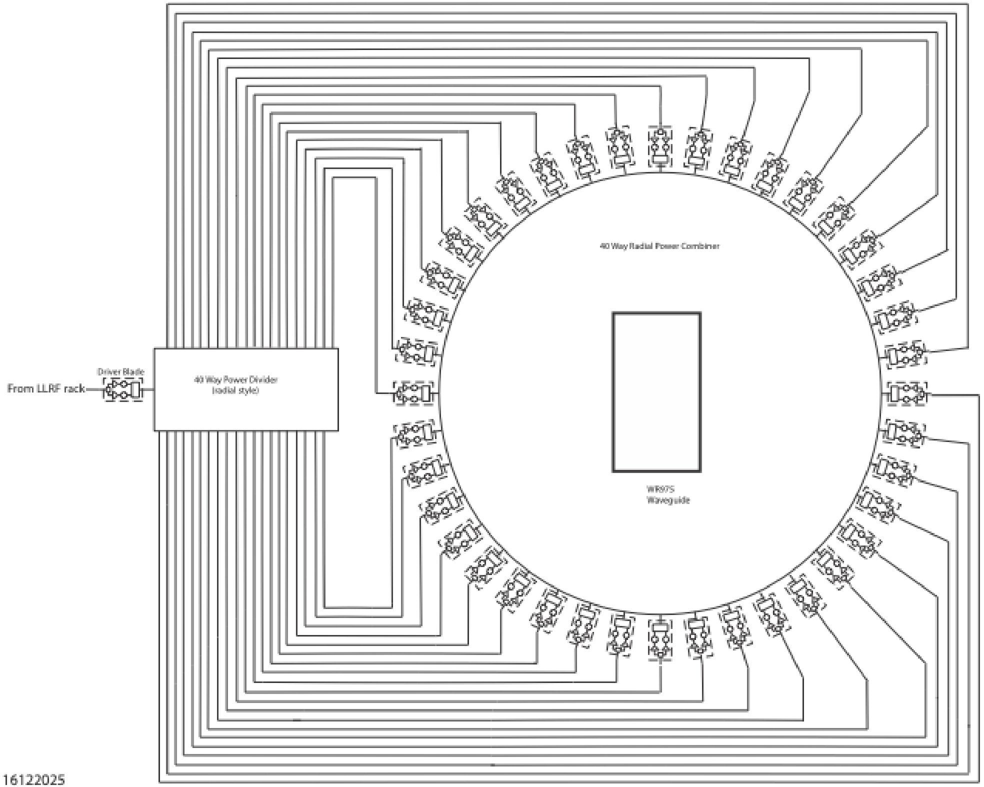
# ¼ Power RF Power Flow

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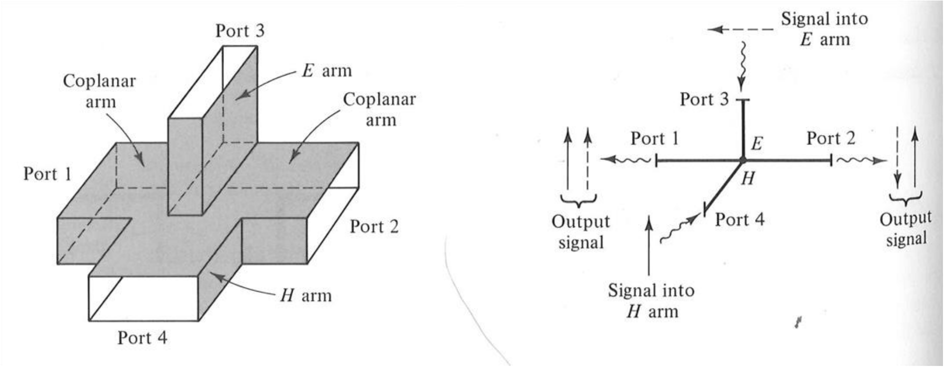
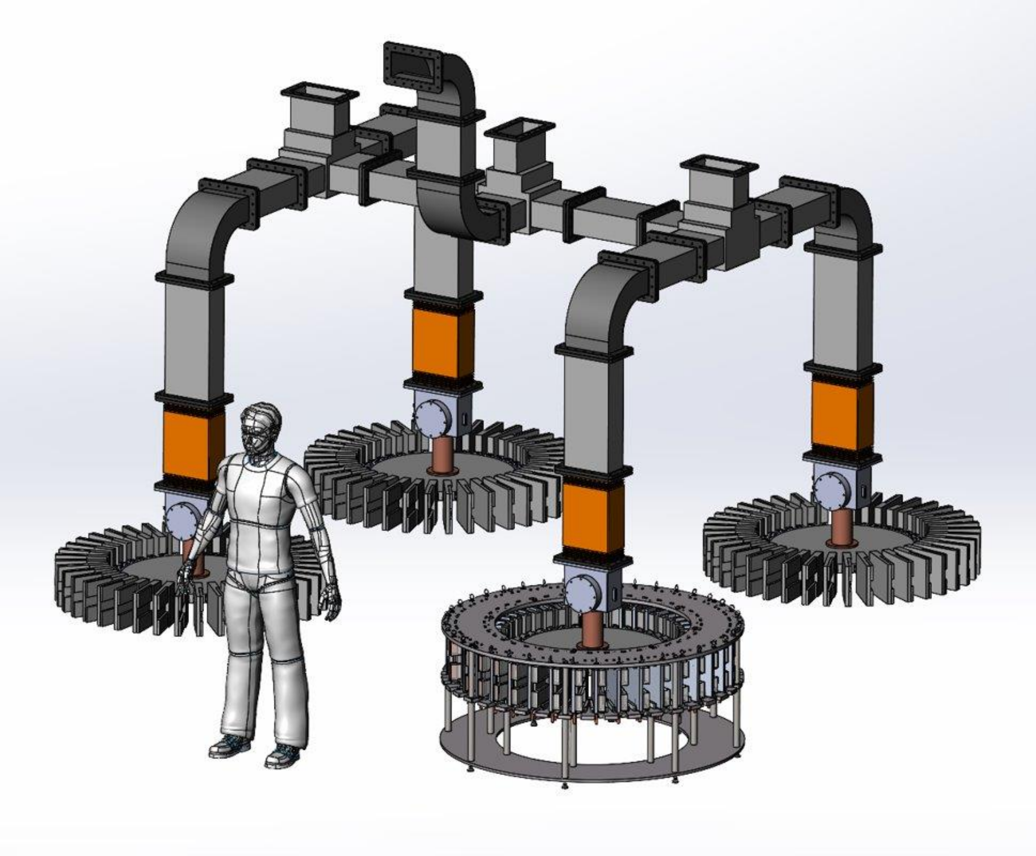
# Magic Tee High Power Combiners



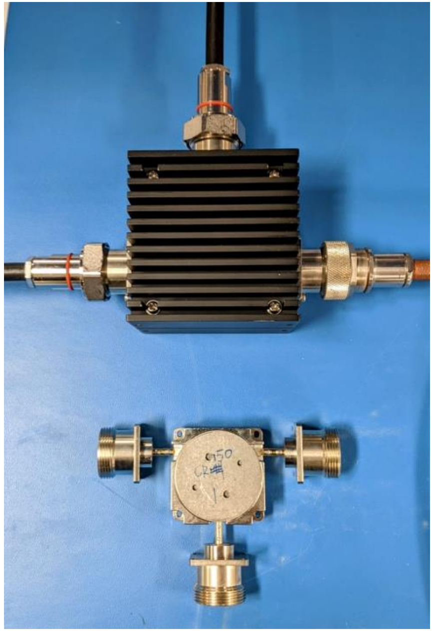

*From Rizzi, Microwave Engineering – Passive Circuits*

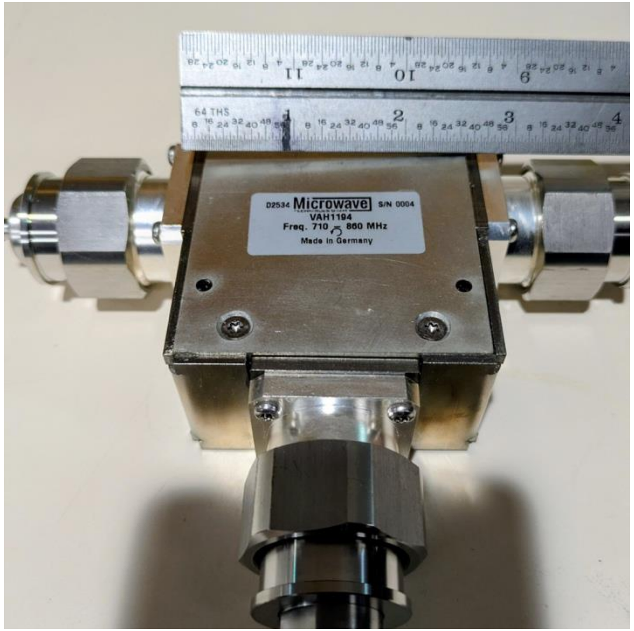
# Full 1.25 MWp Amplifier

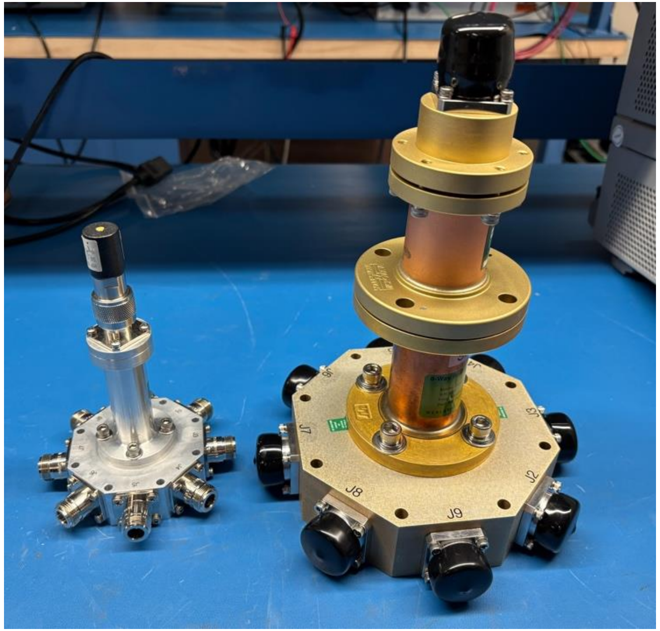
- All elevated aluminum waveguide is lightweight, including magic Tee's
- 3 Water loads not shown, will be near floor, out of way
- Full power circulator is adjacent to shielding shaft to CCL
- 100 VDC power supplied from area of original HV capacitor bank, replaced with LV capacitor bank and AC/DC converters, four per system



# Passive RF Components in Test





- 5 kW circulators vary greatly, even with temperature
- Measuring S-parameters in temperature chamber

8 way radial divider and combiner for 50 kW scaled test this year

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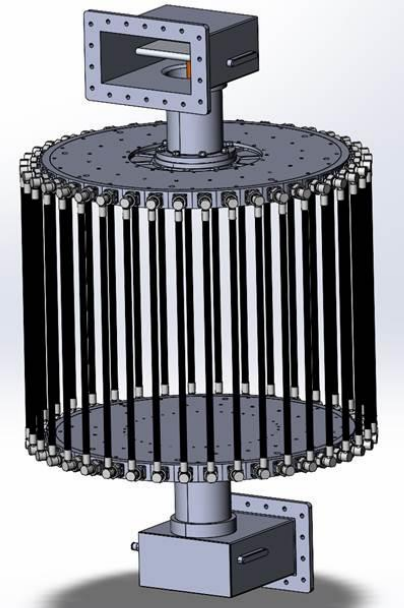
# Passive RF Components – High Power Test



- 40-Way radial power combiner test setup, back-to-back with phase matched cables (10kWp each)
- Will drive this with a klystron and use a water load, in collaboration at SNS
- Thermal test for average power and peak power test for voltage
- Vendor will attend testing

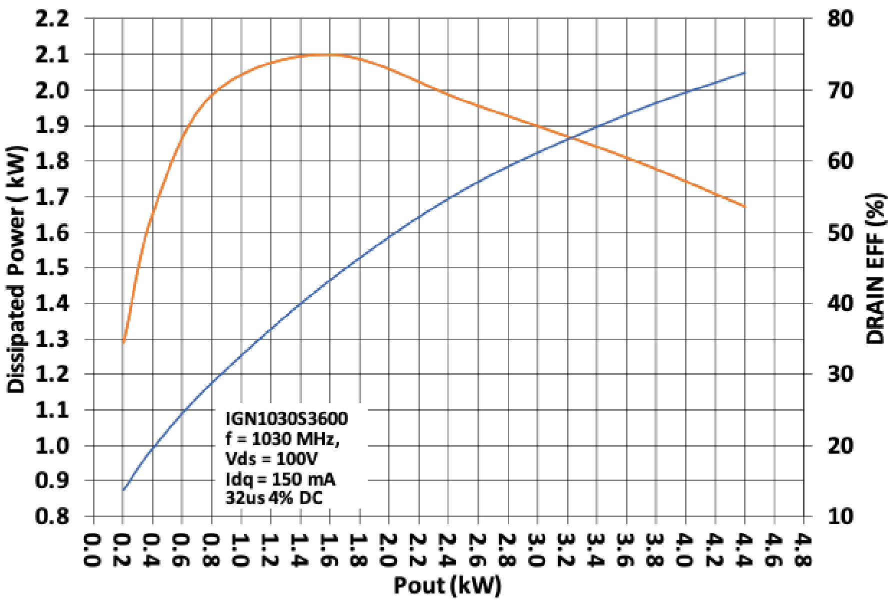
# Varying CCL power requirements at different locations

- **Turning down drive power is a concern for Class AB devices with fixed Vd**
  - **When conditioning a CCL cavity**
  - **Ramping up power slowly**
  - **During accelerator beam tuning**
  - **Normal uneven RF power distribution along linac from physics tune**
  - **Fast power fluctuation for beam loading**

- **Need about 14 dB of output dynamic range for these situations, 50 – 1250 kW**

# GaN Thermal Measurement at Integra Technologies

- **Thermal measurement performed at worst case conditions**
  - This is for another transistor, not IGN815
  - Worst case power dissipation of 1.87kW
  - Flange temperature = 85°C
  - Transient infrared detector used to capture peak temperature during RF pulse

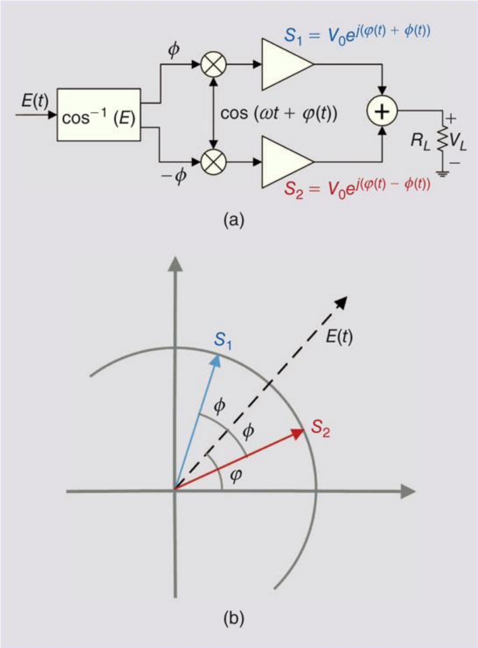



**This property of Class AB amplifiers can kill transistors during power rollback**

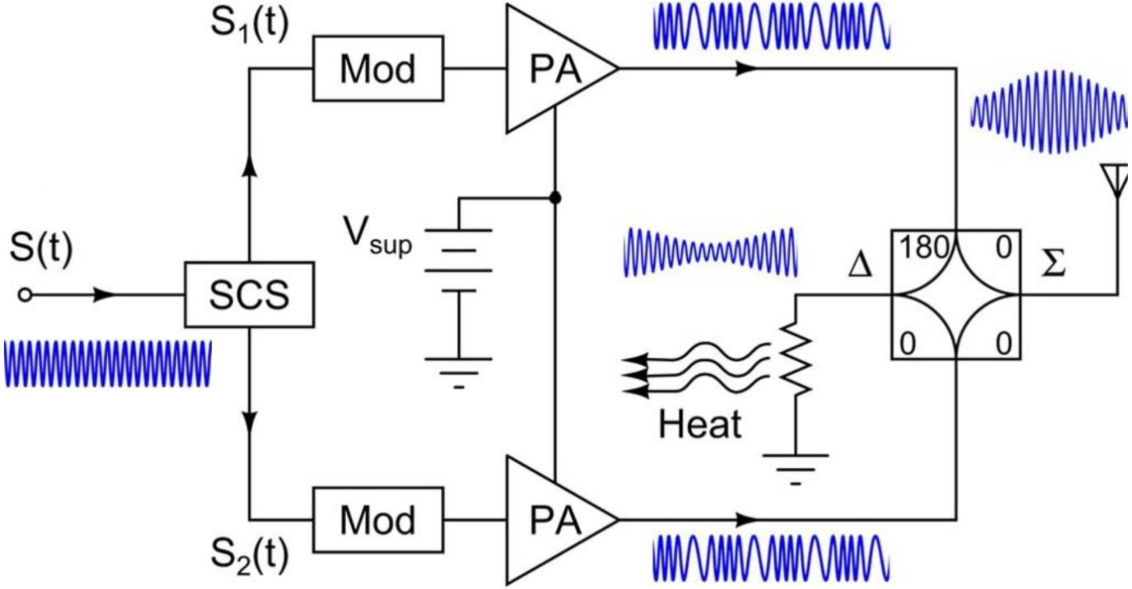
# Techniques for Variable Power to Avoid High $P_d$

- Reduction of Vds below 100 V to keep high efficiency at lower power
  - 20% is safe but it cannot be fast with large power converters
  - How would it be automatic?
  - Below 70 V could cause K factor instability
- Turning off pallets before combiner
  - Must account for reverse power to other pallets
  - Modeling is being done to understand which ones are best
  - Difficult to remove RF driver power from a common driver amp, but could raise gate bias via logic signal to disable output
- Outphasing modulation for fast control, beam compensation

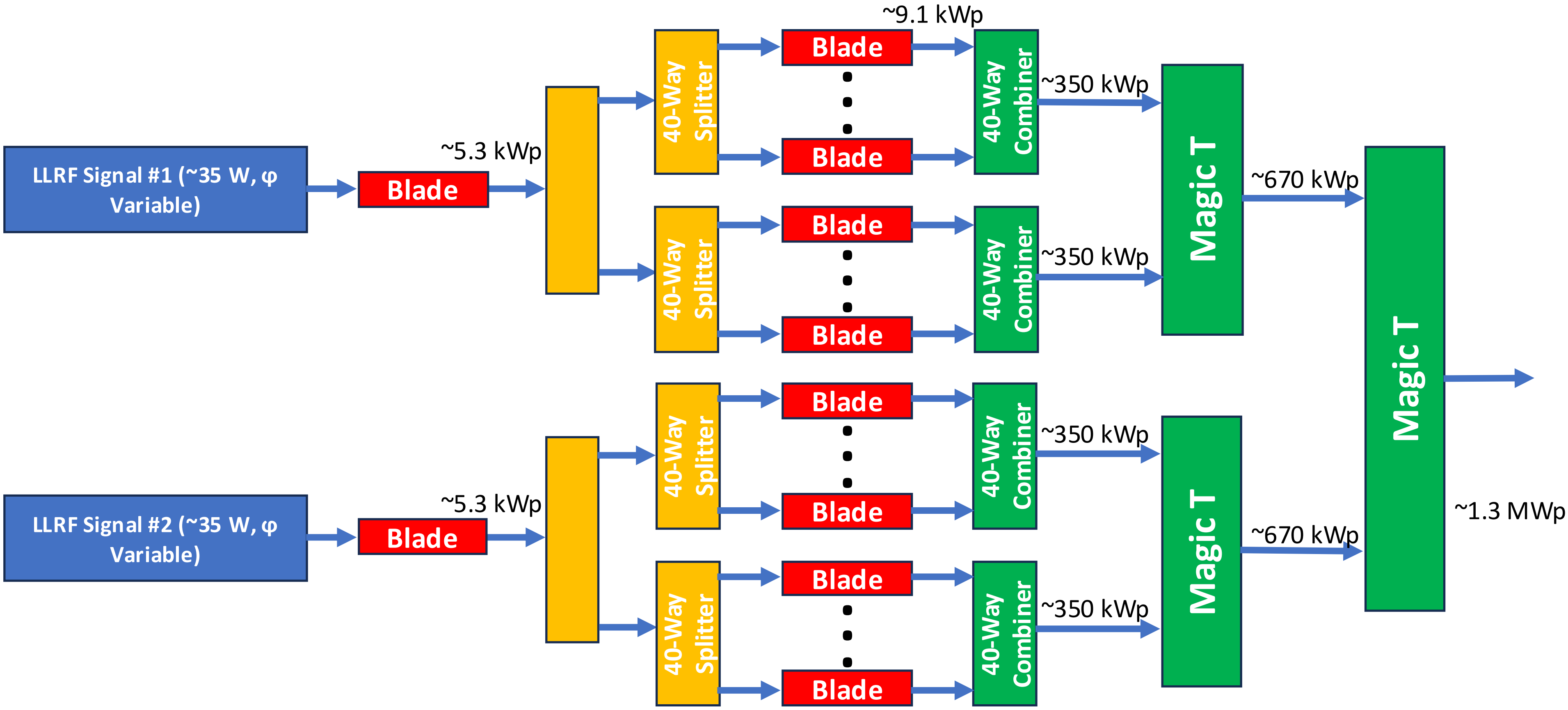
# Outphasing Modulation, with Two PAs driven into Saturation




Vector representation
of outphasing transmitter
(from Barton, IEEE Microwave Magazine, Feb. 2016)




Components before PA are generated in I/Q digital LLRF,
creating two phase modulated signals of constant amplitude
(Adopted from Godoy, IEEE Trans MTT,, Dec. 2009)


LLRF Signal #1 (~35 W, φ Variable)
Blade
~5.3 kWp
40-Way Splitter
Blade
Blade
~9.1 kWp
40-Way Combiner
~350 kWp
40-Way Splitter
Blade
Blade
40-Way Combiner
~350 kWp
Magic T
~670 kWp
LLRF Signal #2 (~35 W, φ Variable)
Blade
~5.3 kWp
40-Way Splitter
Blade
Blade
40-Way Combiner
~350 kWp
40-Way Splitter
Blade
Blade
40-Way Combiner
~350 kWp
Magic T
~670 kWp
Magic T
~1.3 MWp