

“Solid-State HF/6M Power Amplifiers”

(presented at APDXC 2018, Osaka, Japan)

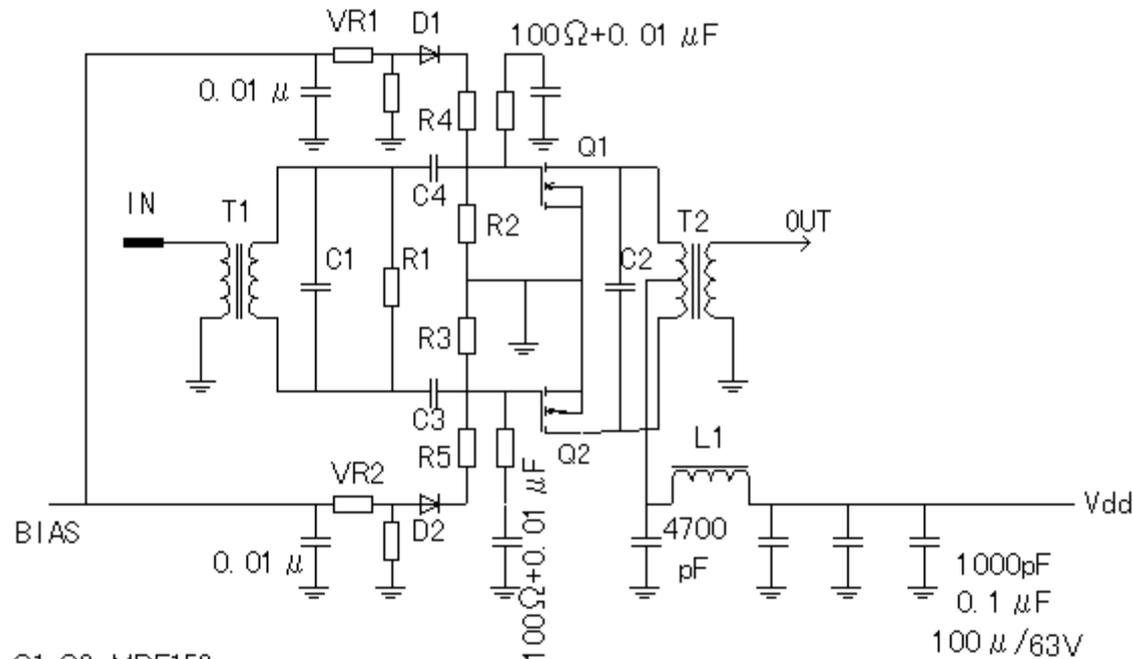
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Solid-State vs. Tube Amp Fundamentals

- Tube and solid-state amplifier design concepts are basically different.
- Tubes require high voltage/moderate current. Typ. 4kV/750mA.
- Solid-state devices use low voltage/high current. Typ. 50V/40A.
- Typical device load resistance $R_L \approx 2k\Omega$ (tube), 3Ω (solid-state).
- Tube amp is single-ended (one tube, or 2-3 tubes in parallel).
- Tuned pi or pi-L output network with working $Q \approx 12$ transforms R_L to 50Ω and suppresses harmonics.
- Cathode-driven triode with broadly-tuned input network or grid-driven tetrode with resistive swamping.
- Solid-state amp is always push-pull (to minimise even harmonics).
- Low impedances dictate broadband base- or gate-driven topology.
- Ferrite-cored input & output transformers match devices to 50Ω .
- Working $Q < 1$; this dictates LPFs (low-pass filters) at PA stage output.

Basic Solid-State PA Building Block



Q1, Q2: MRF150

T1: Ferrite binocular (4:1)

C1: 100pF Dipped Mica

C3, C4: 4700pF, 100V Chip Cap.

R1: 100Ω, 1/4W

R4, R5: 18Ω, 1/4W

T2: Large ferrite binocular 4:1 (Fig. 6.87, 2001 ARRL Handbook)

C2: 330pF × 2 Dipped Mica

R2, R3: 18KΩ, 1/4W

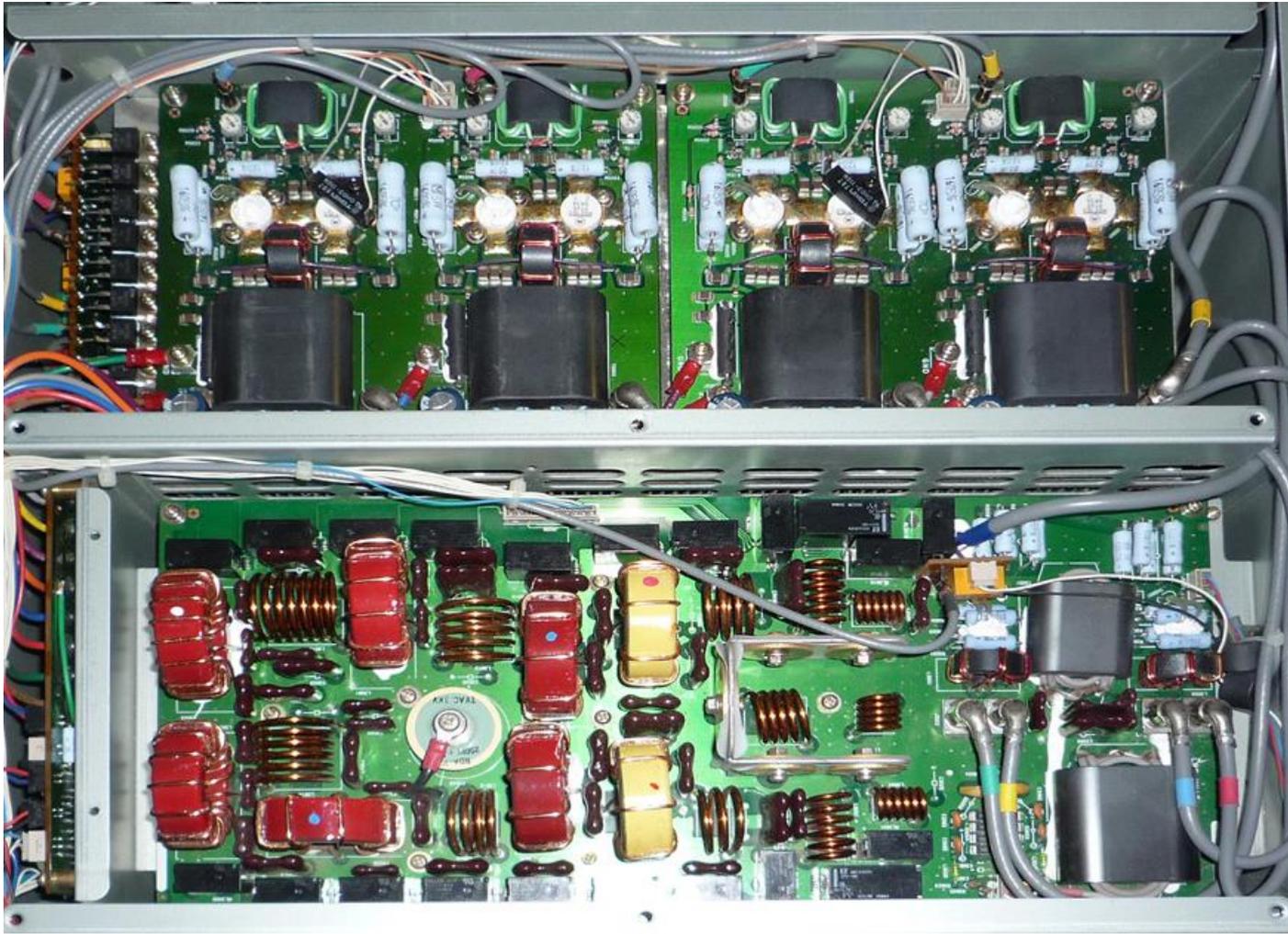
D1, D2: 10D1, 1N4002 or equivalent

This module is rated at 250W output. Two or four identical modules may be combined via an input splitter and output combiner for 500W or 1kW output.

RF Input & Output Transformers

- Transformers are wound on “binocular” 2-hole ferrite cores.
- Bifilar or trifilar windings use miniature Teflon-dielectric coax cable.
- Series R and X of windings \ll power device input or load resistance.
- Cores are sufficiently large to avoid saturation at full RF drive or output.
- Saturation is a major cause of IMD in PA stage.
- Transformers are thermally-coupled to heatsink or placed in cooling-air stream.
 - This removes heat due to iron loss.
- PA modules are combined with input splitter and output combiner. These are transformer hybrids (3-port for 2 modules, 5-port for 4 modules).
- Hybrid transformers are of same construction as input/output transformers.
- Splitter/combiner windings are terminated in 50Ω to prevent core saturation or hybrid imbalance (over-dissipation in hybrid balancing resistors).
- Splitter or input transformer primary presents 50Ω load to exciter.
- A pad at the RF input stabilises input impedance and sets system power gain.
- Exciter’s auto-tuner is never required when driving a solid-state amplifier.

Example of solid-state amp (Yaesu Quadra)



Top: 1kW PA stage (4 X 250W). Bottom: LPFs for all bands 160 - 6m.

Harmonic (Low-Pass) Filters

- The combiner output is fed to a bank of low-pass filters (LPF).
- These filters are bandswitched, and reduce harmonic and spurious emissions to levels required by radio regulations (typ. ≤ -46 dBc).
- LPF are usually Chebyshev networks (high attenuation & steep roll-off near cutoff frequency).
- Filters are implemented using air-wound and ferrite-cored inductors and high-Q, low-loss, high-current capacitors (e.g. silver-mica).
- One filter per band/range; filters are selected via miniature relays.
- Cooling air is routed via the filter box to remove heat due to losses.
- Filter insertion loss typically 0.5 – 1 dB in the passband.
- Firmware lockout prevents band changes during transmit.
- A reflectometer at the filter-bank output provides forward- and reflected-power signals for ALC, Po/VSWR indication and ATU control.
- A second reflectometer at the filter-bank input extends an alarm signal if the drive frequency and the selected band are mismatched.

Auto-Tuner (ATU) and T/R Relays

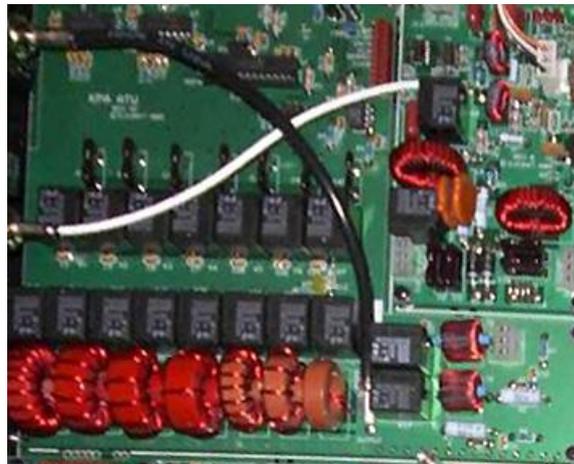
- Many solid-state amplifiers are fitted with an internal ATU.
- The ATU is usually a T-network (series C – shunt L – series C).
- Two topologies are popular: (1) Air-variable C's driven by stepper motors, in conjunction with relay-switched fixed C's and L's, and (2) LC combinations switched entirely by relay chains according to a firmware algorithm.
- A phase detector, or a return-loss bridge working in conjunction with the reflectometer between the LPF bank and ATU, provides fine tuning.
- Typical matching range: 16.7 - 150Ω (load VSWR ≤ 3:1).
 - ATU insertion loss: 0.5 dB when matched to 1.5:1 VSWR.
- During the tuning cycle, the PA stage can be bypassed via relays and a pad inserted in the signal path to minimise on-air interference.
- The PA and ATU can also be bypassed separately.
- In some designs, a reflectometer at the ATU output extends a shutdown alarm in the event of antenna/feedline failure.
- Miniature high-speed relays at the ATU output and the splitter input provide transmit/receive switching.
 - Some designs signal the exciter to cut drive during T/R transitions, for QSK CW keying.

ATU Examples

Motorised C's
(Yaesu Quadra)



Relay-chain type
(Elecraft KPA1500)



Solid-State Amplifier Design Considerations



- Power device types:
 - MOSFET (metal-oxide semiconductor field-effect transistor) e.g. MRF150 (250W/pair, $V_{DD} = 50V$).
 - BJT (bipolar junction transistor) e.g. MRF448 (200 – 250W/pair, $V_{CC} = 40V$).
 - LDMOS (Laterally Diffused MOSFET) e.g. MRF1K50H (1 – 1.5kW/device, $V_{DD} = 50...65V$).
- Generally, MOSFETs offer superior power gain, gain-bandwidth product and linearity as compared to BJT's. All current designs use MOSFETs or LDMOS.
- Typical IMD_3 at rated output: -26 to -29 dBc (32 – 35 dB below 2-tone PEP).
 - Amplifier output **must** be terminated in 50Ω resistive for optimum linearity.
 - Tube amplifier $IMD_3 \leq -34$ dBc (40 dB below 2-tone PEP).
- Typical efficiency (RF output/DC input): 45 – 50%.
 - Compares favourably to tube amp if we include tube heater and screen power input.
- Class AB operation ($180^\circ < \text{conduction angle} < 360^\circ$).
 - Gate bias set for minimum crossover distortion.

Design Considerations (cont.)

- Rated Power Output (3 classes: 500W, 1kW, 1.5 – 2kW).
 - 500W: 2 MOSFET pairs w/splitter & combiner.
 - 1kW: 4 MOSFET pairs w/splitter & combiner.
 - 1.5 – 2kW: Single LDMOS device, no splitter or combiner required. This eliminates hybrid insertion loss and reduces passive IMD (PIM) in transformer cores.
 - Parallel connection of MOSFET devices can cause destructive VHF parasitics.
- Power Gain (RF output/drive power): MOSFET \approx 20 dB, LDMOS 20 – 25 dB.
 - System power gain = device power gain – loss in transformers, hybrids, input pad
 - Typical values (14 MHz): 15 dB (for US FCC compliance), 20 – 23 dB other versions.
 - Device power gain rises \approx 2 dB at 3.5 MHz, falls off \approx 2 dB at 28 MHz (4 dB at 50 MHz).
- Reduced-Power Operation: lowering V_{DD} is best method.
 - Amp should always be driven to just below saturation for min. crossover distortion.
- Full Break-in (QSK) CW operation:
 - T/R relays are miniature high-speed types.
 - Exciter carrier-on timing protects against hot-switching.
 - Some amplifiers provide a transmit inhibit signal to exciter. This cuts drive until T/R relays have settled.

Control & Monitoring Features

- Microprocessor controller functions: monitoring, control, protection and metering.
- Monitoring
 - DC supply voltage V_{DD}
 - Input current I_D (total and per-module)
 - RF drive power and frequency
 - RF power output per module
 - Total forward and reflected power (measured at LPF output), VSWR calculation
 - Reflected power at combiner output and ATU output
 - RF power device case temperature
 - Alarm indication from internal power supply
- Control
 - T/R switching & bias gating
 - Processes band information from exciter
 - Bandswitching (LPF selection relays)
 - Antenna selection (in some designs)
 - ALC line (FWD/REF PWR and other parameters control ALC voltage to exciter)
 - ATU control; can be either static (remain on setting until retuned) or dynamic (track load changes)
 - Power management (power-up, shutdown)
 - Fans

Metering & Protection Features

- Metering:
 - DC supply voltage V_{DD}
 - Total input current I_D
 - RF power output (RF drive power when PA stage bypassed)
 - Load VSWR (some amps present a graph of ATU input & output VSWR vs. frequency)
 - ALC level
- Protection:
 - Excessive V_{DD} and/or I_D ; also I_D imbalance between modules
 - Safe device temperature exceeded; cooling-system failure
 - Overdrive (excessive forward power) & excessive reflected power (VSWR too high)
 - Insufficient power gain; also power-gain imbalance > 3 dB between modules
 - ATU out of range (load VSWR > 3:1)
 - Incorrect band selection (exciter and amplifier not on same band)
 - “Brute-force” diode overshoot protection at RF input (in some designs)
- 3-stage mismatch protection:
 - VSWR > 1.5:1: Drive foldback via ALC line
 - VSWR > 2:1: Power output reduced by 3 dB
 - VSWR > 3:1 or gross mismatch at ATU output: Amplifier forced to standby state

Automatic Band Selection

- There is no standard protocol. Each OEM has its own method:
 - Exciter presents variable analogue voltage to amp; a discrete voltage represents each band.
 - Exciter presents 4-bit parallel binary band code to amplifier.
 - Exciter transmits band data packets to amp via a serial line or LAN interface.
 - Amplifier requests carrier from exciter, counts carrier frequency and sets itself up accordingly.
- Once the controller has determined the band:
 - It selects the correct LPF for that band by operating its relays.
 - It sets the ATU (if fitted) to the same band.
 - If aware of the drive frequency, it presets ATU to the closest stored tuning point.
 - It sets up the antenna selection stored for that band.
- Avoid transmitting during a tuning or band-change cycle.
 - This will allow the amp to drop back to standby state once the cycle is complete.
- Auto lockout if drive frequency does not match selected band.

Automatic Level Control (ALC)

- The ALC line is a solid-state amplifier's first line of defence.
 - ALC feeds back a control voltage (typ. 0 to -4V) to gain-controlled stages in exciter.
 - More negative ALC voltage = lower drive power.
 - ALC limits amp output to a preset value without causing distortion, and
 - reduces drive when amp's protective features detect an anomalous condition.
 - Examples: load mismatch, over-temperature, excessive drive power.
 - ALC should have short attack time to minimise overshoot, and release time should be sufficiently long to prevent modulation of ALC loop by SSB voice peaks or CW keying.
 - Typical ALC time constants: 1 – 2 ms attack, 0.25 – 2s release.
 - Amplifier should provide an ALC level adjustment to set output levelling point.
 - ALC should be set in RTTY or CW mode for levelling at rated power output, and drive power should then be set such that levelling just occurs. This will prevent “ALC compression” which can cause distortion and splatter.
 - As IMD3 increases by 3 dB, and IMD5 by 5 dB, for each dB above rated output, the design rating should never be exceeded.
 - To ensure a clean signal and avoid costly damage, proper ALC setup is absolutely mandatory when using a solid-state amplifier. Never use exciters without ALC inputs!

External Interfaces

- RF input: often 2 selectable inputs provided.
 - Separate PTT and ALC ports, and ALC adjustment, for each input port.
- RF output: 1 port, or 2 to 4 selectable or programmable antenna ports.
- ALC port (usually 0 to -4V, negative-going), often on RCA jack.
- PTT (SEND or keying) port, often on RCA jack.
 - Low-level (TTL or 12V/1-2mA; direct connection to exciter SEND line without a buffer.
- TX Request port (on some amplifiers):
 - Keys exciter to obtain tuning carrier; amplifier counts carrier frequency for band selection or ATU tuning. This feature supports exciter and amp of different makes.
- Band Data input: refer to Slide 13.
- TX inhibit for QSK CW (if supported by exciter): refer to Slide 10.
- RF sampler output for exciters with pre-distortion linearisation
 - on newest amps; RF sampler at LPF output.
- Interface lines may be grouped in multi-pin sockets.
- Ethernet (LAN) port for band selection, remote control etc. (on newest amps).

Power Supply Unit (PSU)

- PSU may be internal or external.
- Both switch-mode and linear PSUs are encountered; almost all modern solid-state amps employ a switch-mode PSU (much higher efficiency, reduced size & weight).
- Fully EMC-qualified OEM switch-mode PSUs designed for server or general-purpose use are popular with amplifier manufacturers.
- Typical PSU ratings: 40V/25A for 500W amp, 50V/50A for 1kW, 65V/50A for 1.5kW.
- AC mains voltage rating 100-250V; 230-240V mains operation preferred.
 - Better regulation with 230-240V mains improves linearity.
 - PSU should be fitted with dedicated 2-pole mains breaker.
- DC output must have 5% or better regulation for optimum linearity.
 - Bias supply must be absolutely stable and free from RF or envelope modulation, for best linearity. To reduce idle dissipation, bias is off during standby.
 - RF-sensing electronic bias switching is not used in solid-state amplifiers.
- PSU should incorporate adequate forced-air cooling.

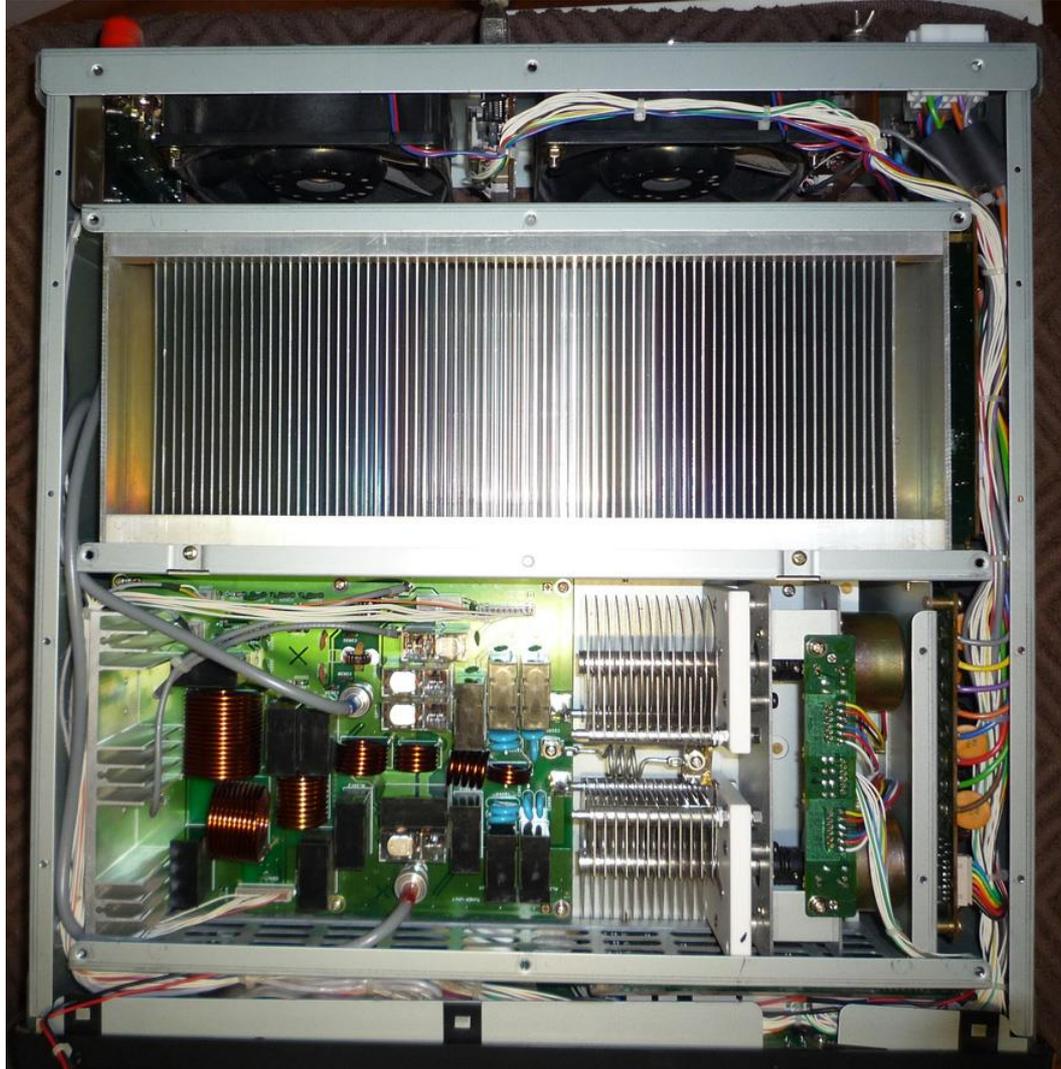
Thermal Packaging and Cooling

- Efficiency of a solid-state HF/6m amplifier $\approx 40 - 50\%$.
 - Thus, PA cooling system must be capable of dissipating at least one-half the DC input power.
 - Cooling system must keep device case temperature at $70 - 80^{\circ}\text{C}$ at 25°C ambient, for a 30-minute SSB transmission or a 5- to 10-minute CW transmission at rated output. (ICAS ratings).
 - Contest operation, or at higher ambient temperatures, necessitate a larger cooling area and greater air-flow.
- The cooling system can consist of a flat, planar heatsink with fans blowing air across it, a cylindrical heatsink structure with a large fan at one end, a circulating-water system with a fan-cooled radiator or a thermodynamic heat-pipe system.
- The cooling fans can run continuously at a constant speed, or run at half speed in standby and at full speed during transmit.
- As the ATU can dissipate 125W at 1kW output, it is often cooled by a dedicated fan in the ATU enclosure.
- A thermal sensor signals the controller to reduce drive and/or go to standby when the safe PA device temperature is exceeded.
 - An air-flow switch can shut down the amp in the event of fan failure or clogged air-vents.

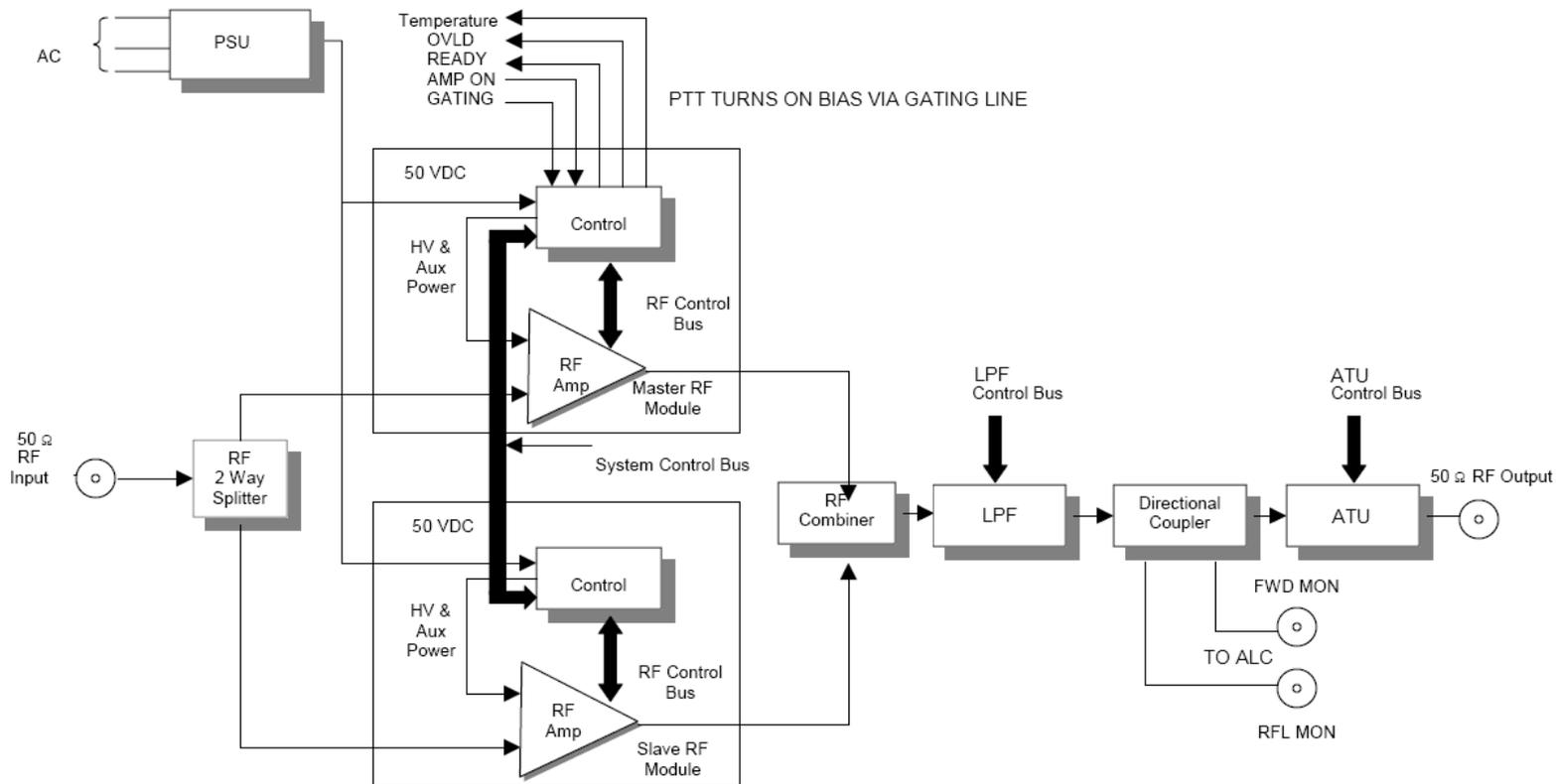
Electronic & Mechanical Packaging

- All printed-circuit boards must be top-quality FR4/G10 fibreglass, at least 3mm thick. Solder-plated tracks should be sufficiently thick and wide to safely carry the very high RF and DC currents in the PA stage.
- Low-inductance layouts should be used throughout, except for on-board inductors.
- Push-pull circuits should be reasonably symmetrical in layout.
- RF component lead lengths should be as short as practicable.
- Shielding: Each amplifier subsystem should be totally enclosed in its own shielded compartment within the chassis.
- Power and control leads should enter these enclosures via feedthrough capacitors. RF interconnect cables should have their braiding grounded at their entry points. Lead dress should be observed.
- These shielding measures will preserve RF integrity, minimise internal RF feedback and maintain regulatory EMC compliance.
- Air intakes and outlets must be of sufficient area to ensure proper airflow.
- Any dust filters should be easily accessible for cleaning.

Yaesu Quadra PA Heatsink & ATU



Simplified Block Diagram



SIMPLIFIED BLOCK DIAGRAM OF TYPICAL SOLID-STATE HF AMP (2 MODULES)

T/R switching omitted for clarity

List of current HF and HF/6m solid-state amplifiers

Brand	Model	Bands	Devices	V _{DD}	Pwr out W	Drive W	ATU	PSU	Price \$	Remarks
Icom	IC-PW1	HF+6m	8 MRF50	48V	1000	≈30	Y	SMPS	4900	Auto w/Icom
Yaesu	Quadra		8 MRF150	48V	1000	≈ 60	Y		4300	Auto w/Yaesu ¹
Acom ²	600S		2 MRFE6VP63 00H	48V	600	≈ 20	N		2800	Auto via CAT
	1200S		2 BLF188	48V	1299	≈ 50	N		3500	Auto via CAT
Elecraft	KPA500		2 VRF2933	60V	500	≈ 30	KAT500	Linear	2400	CAT/RF sense
	KPA1500		2 BLF 188	60V	1500	≈ 50	Y	6000	4300 ³	CAT/RF sense
SPE	1.3K-FA		1 LDMOS	50V	1300	≈ 45	OPT	SMPS	5000	CAT/RF sense
	1.5K-FA		1 LDMOS	60V	1500	≈ 50	Y		6700	
	2K-FA		6 MRF151G	50V	2000	≈ 70	Y		7000	CAT/LAN
Flex	PG-XL		2 MRF1K50H	50V	2000	≈ 50	OPT		6600	Auto via CAT
Hilberling	HPA-8000A54	1 LDMOS	50V	1000	≈ 50	Y	3800		RF sense	
Palstar	LA-1K	2 MRFE6VP56 00H	50V	1000	≈ 50	N	2100		EB-104	
Ameritron	ALS-600	HF	4 MRF150	50V	600	≈30	N	Linear	2100	EB-104
	ALS-1300		8 MRF150	50V	1200	≈50	N	SMPS	2900	2 X EB-104

Notes:

1. RF sense with non-Yaesu exciter.
2. No ALC output.
- 3 With ATU. \$700 less w/o ATU.

References for further study

1. <http://www.ab4oj.com/quadra/sshfamp.html>
2. A. Farson VA7OJ/AB4OJ, “What Makes a Good Solid-State Amplifier for the Contester”, Parts 1 & 2, ARRL NCJ, March-April and May-June 2018.