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Technical Requirement Specification
7 kWatt, 325 MHz RF Power amplifier for SSR1 Cavity provided by BARC and Fermilab

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1. Introduction

The 800 MeV, 2 mA Superconducting (SC) linear accelerator (LINAC) is at the heart of the Proton Improvement Program – II (PIP-II) being developed at Fermilab. With modest improvements to existing main injector and recycler accelerators, the superconducting linac (called as SCL) will inject into the Booster, Recycler, Main Injector accelerator chain providing MW class beam for the long baseline neutrino facility. A schematic showing PIP-II linac technology map of this accelerator is shown in the Figure 1. Single spoke resonator cavities with β (0.22 and 0.47) are planned to be used, which utilizes 325 MHz of RF power. Under "Indian Institutions and Fermilab collaboration (IIFC), DAE will be designing and developing the solid-state RF power amplifier at 325MHz. Advances in solid-state Field Effect Transistor (FET) device manufacturing have enabled solid-state amplifiers to challenge tube amplifiers at the required power levels, albeit at higher acquisition costs. The advantages of solid-state amplifiers over klystrons are multiple i.e. modularity, low voltage operation, graceful degradation etc.

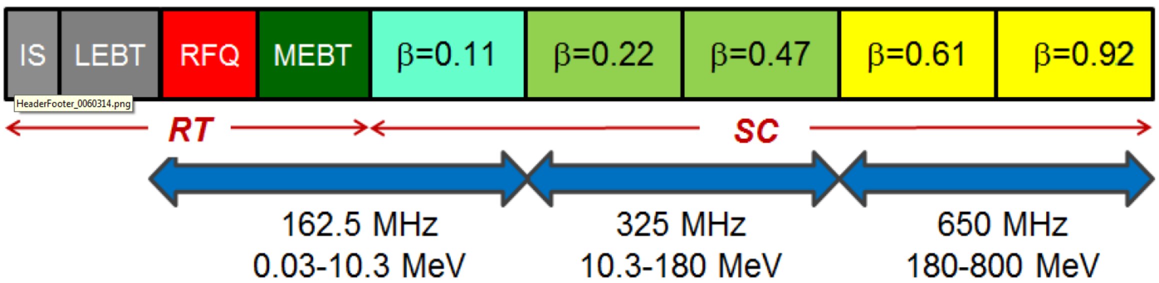


Figure 1: PIP-II Linac Technology map

The accelerator will initially be pulsed up to 20 Hz with a minimum pulse length of 6msec for injection into the Fermilab booster accelerator, but the PIP-II design will be capable of CW beam operations to support future, high proton flux, experimental targets.

The current PIP-II design requires two levels of RF power operating at 325 MHz for the single spoke resonator section of the linac. They are 7 kW for the SSR1 and 20 kW for the SSR2 cavities. This document is concerned solely with the SSR1 cavities requiring 7 kW RF power.

2. Scope and supporting material

This document discusses about the technical requirements of 7 kW, 325 MHZ RF power amplifier that provides RF power to the SSR1 cavities of PIP-II linac. Detailed technical requirements are described under following items

1. Interfaces: Hardware and electrical
2. Architecture of 7 kW RF Power amplifier
3. Hard wired interface signals
4. Technical specifications of 7 kW RF power amplifier
5. Interlock and protection system flow diagram
6. Quality assurance plan and acceptance test procedure

Supporting materials for this document are R&D work at BARC [1-2], functional requirement specifications (FRS) of 7kW 325 MHz for SSR cavities, IEC standards listed in QAP/ATP.

3. Interfaces

1. The RFPA and its sub-systems will be 19” rack mountable. Maximum depth of the sub racks including external rear connectors cannot exceed 27 inches (68.6 cm). Only RF output with directional coupler may exceed this dimension. Fermilab will provide the rack with dimensions shown in the drawing attached as Appendix A
2. 3 phase 4 wire (Delta with ground) 480 VAC, 60Hz, input to the RFPA will be made available by Fermilab to the amplifier input.
3. Fermilab will provide the electrical cord and wall plug connector. 32A breakers will protect input power. 480 VAC should have terminal blocks (internal to the amplifier) for connections.
4. The amplifier will provide 1” NPT standard, male connectors for water supply (inlet and outlet). The water connections should be placed on the rear panel at the bottom. Appropriate drain and vents for the water system are required. The water system will be capable of delivering 32lpm (8.5 gpm) minimum up to 125psi. Adequate flow must be guaranteed with a minimum of 60-psi differential pressure.
5. Output RF power will be connected with a 50 Ohm, 3 1/8” EIA standard flange. The RFPA will drive a circulator (provided by Fermilab) with a VSWR < 1.4:1 (15 dB return loss worse case) over the operating range of the amplifier.
6. RF input will be 50 Ohm, N connector (F) standard, with input return loss <-15 dB minimum. Maximum available power from LLRF system is 10dBm. Connector will be placed on the rear panel.
7. Signals from and to RFPI will be available on BNC while signal from and to control system will be on D type connector. Details of the signals can be found in the section 5a and figure 6, 7a, 7b and 8 of this document. Connections on the SSRA will be a BNC connectors.
8. High-level signals represent OK status while low level signal represent fault state.
9. Signals from RFPA to RF protection Interlock (RFPI) is “SSA Ready/Fault” and signal from RFPI to RFPA is SSA_INHIBIT and DC_INH. These signals will be on BNC connector. Both these signals are 50-ohm TTL signals. So these signal need suitable drive and termination (50Ohm) requirement.
10. “SSA_Ready / fault” output status from RFPA to control system will be active high. SSA_Ready / fault, going to control system will be provided on D type standard connection on front panel of the VME based IPMS. See typical output circuit in figure 7a and 7b.
11. “Safety Permit” input from Safety interlocks system shall be a contact signal, on same D type standard connector (from control system) at rear panel. See typical input circuit below. In case of open contact, the amplifier will be blanked/by removing all power, which will disable RF power.
12. “ON/OFF”, “Reset”, and “Trigger/gating” inputs from control system shall be active high, D type standard connection rear panel. They should be 50-Ohm drive capable. See typical input circuit in figure 7a and 7b. It is preferred that these features should also be achieved via Ethernet inside in SSRA.
13. All other controls and diagnostics will be accessible through a standard Ethernet port using MODBUS/TCP or EPICS based communication protocol.
14. All the sub-systems of the RFPA will be 19” rack mountable design.

15. Installation of the RFPA sub-modules in the 19” rack at Fermilab will be done with the help of Fermilab personal according to the procedure supplied by BARC/DAE.

4. Architecture of 7 kW, 325 MHz RF Power Amplifier

Amplifier architecture is shown in the block diagram representation in Figure5. It illustrates the signal flow and interface with external systems that were specified in the Functional Requirements Specification. It also illustrates the planned system architecture and sub-system interconnects. The key features of this architecture are high output power (7 kW) using low power PA modules (1 kW), modular design and graceful degradation.

- This architecture decision creates a new subset of functional requirements not listed in the original FRS document. The purpose of these requirements is to optimize the reliability of the system in light of the approved architecture. These requirements include interlock and protection (monitoring) system where each sub-amplifier will provide information on its status/fault condition on to the external control interface. The identifier for each sub-amplifier will be based on its physical position in the amplifier.
- The sub-amplifier design will have its own specifications requirements, which will include interchangeability within the amplifier system.
- Documentation of sub-amplifier installation procedures should be sufficient for Fermilab maintenance personnel to perform assembly and replacement.

4.1 1 kW RF Power Amplifier module, 325 MHz and its interlocks

The 7 kW, 325 MHz RF power amplifier design is based on solid-state device technology (LDMOS). The complete amplifier is designed and developed around the 1 kW, 325 MHz power amplifier module. These amplifier modules are designed to achieve DC to RF efficiency $\geq$ 68%, power gain $\geq$20 dB, harmonics content $\leq$ -25 dBc, spurious noise $\leq$ -60 dBc, group delay of $\leq$ 100 ns and phase shift over 10 dB dynamic range $\leq 15^{o}$. Except for efficiency and gain, these same specifications apply to the complete amplifier. Amplifier design includes water-cooled and air-cooled sub systems for thermal management. Amplifier design also addresses the amplifier’s reliability and repeatability in production as one of the most important parameters to achieve good combining efficiency. Output power from these 1 kW, 325 MHz amplifier modules is then combined to achieve 7 kW, 325 MHz RF power output at 1 dB compression. Combiner/divider technology used for this amplifier is Wilkinson type power divider and combiner without internal resistors. Power divider is a micro-strip based component while power combiner is based on coaxial technology, which can handle large amount (10 kW@ 325 MHz) of RF power. All the design information for the 7 kW, 325 MHz RF power amplifier can be found in the work from J K Mishra et.al [1].

These amplifiers have been designed and tested under controlled environment. Thermal management inside the amplifier is closely linked to the input cooling and ambient conditions to the amplifier. Power amplifier design [1] needs to be qualified for the water-cooling and ambient conditions specified in the Functional Requirement Specifications [3].

Amplifier modules are protected from reflected power using an integral circulator inside the PA modules. 7 kW, 325MHz amplifier will be protected from the reflected power by employing external circulator at the amplifier output (provided by Fermilab). Other protections for the PA modules are mentioned in the Interlock, protection and monitoring system (IPMS).

IPMS have been implemented with VME64x based controller (MVME5500) in a 7 U VME crate, which will be compatible with 19" rack. This design will be implemented using FPGA based cards. Mezzanine card approach on VME carrier card has been used to design this system for modularity and easy upgrading. Fast and slow signals are processed using different cards/circuits to ensure safe and reliable operation. Main functions of IPMS are as follows

1. Initialize amplifier ON/OFF sequence
2. Acquiring, processing, logging and displaying the amplifier data.
3. Protect the amplifier from faulty operating conditions
4. Handshaking of signals with external systems for amplifier protection.
5. Facilitate communication with external systems through standard communication protocols i.e. (EPICS)
6. Stores the amplifier operating parameters for diagnosis purpose.

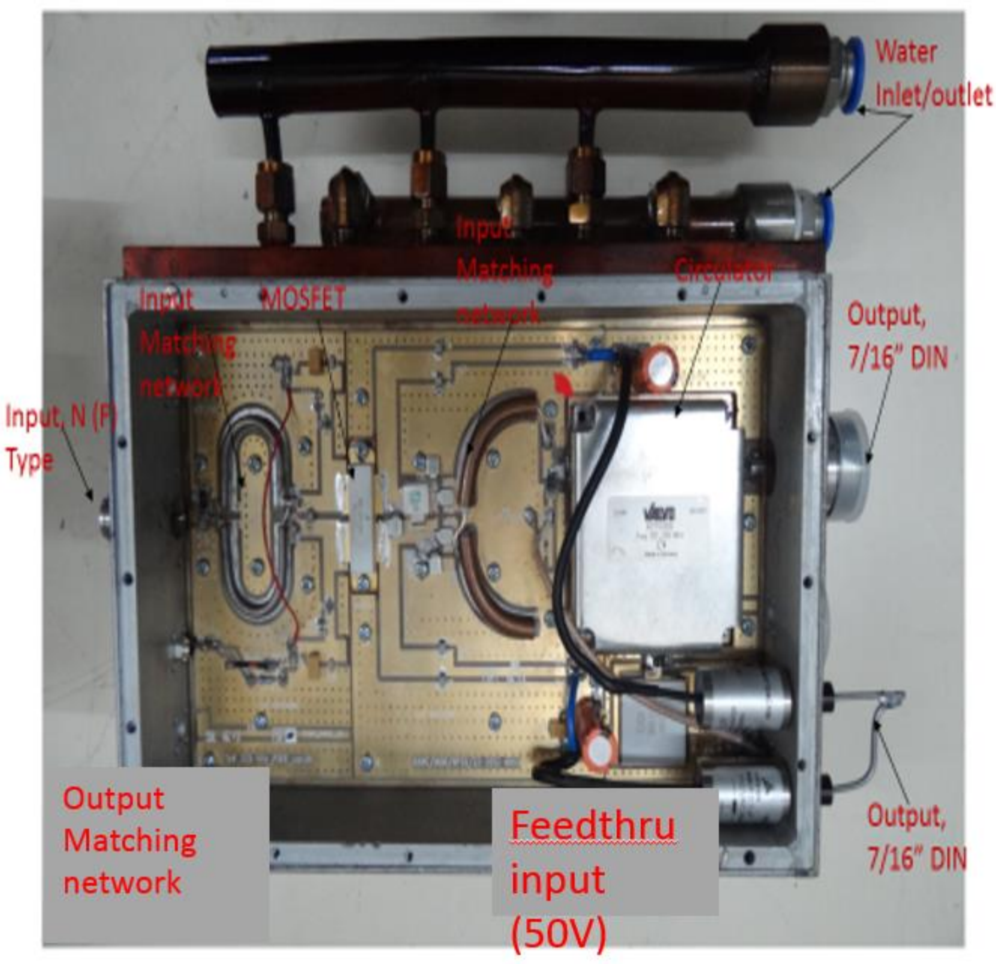


Figure 2 Existing 1 kW amplifier module design

Photograph of existing design for 1 kW amplifier module is shown in Fig 2. This design has been used in 3 kW, 325 MHz amplifier (BARC-DAE), which has been tested at Fermilab during Oct – Dec 2015.

Amplifier heat sink design has been modified to include better RF shielding and grounding, improved water connections and making compact amplifier module without compromising the thermal management issues. Figure 3 shows the exploded view of the heat sink. One heat sink houses two 1 kW amplifiers @ 325 MHz. Electronics of these two amplifiers are housed on the two copper heat plates.

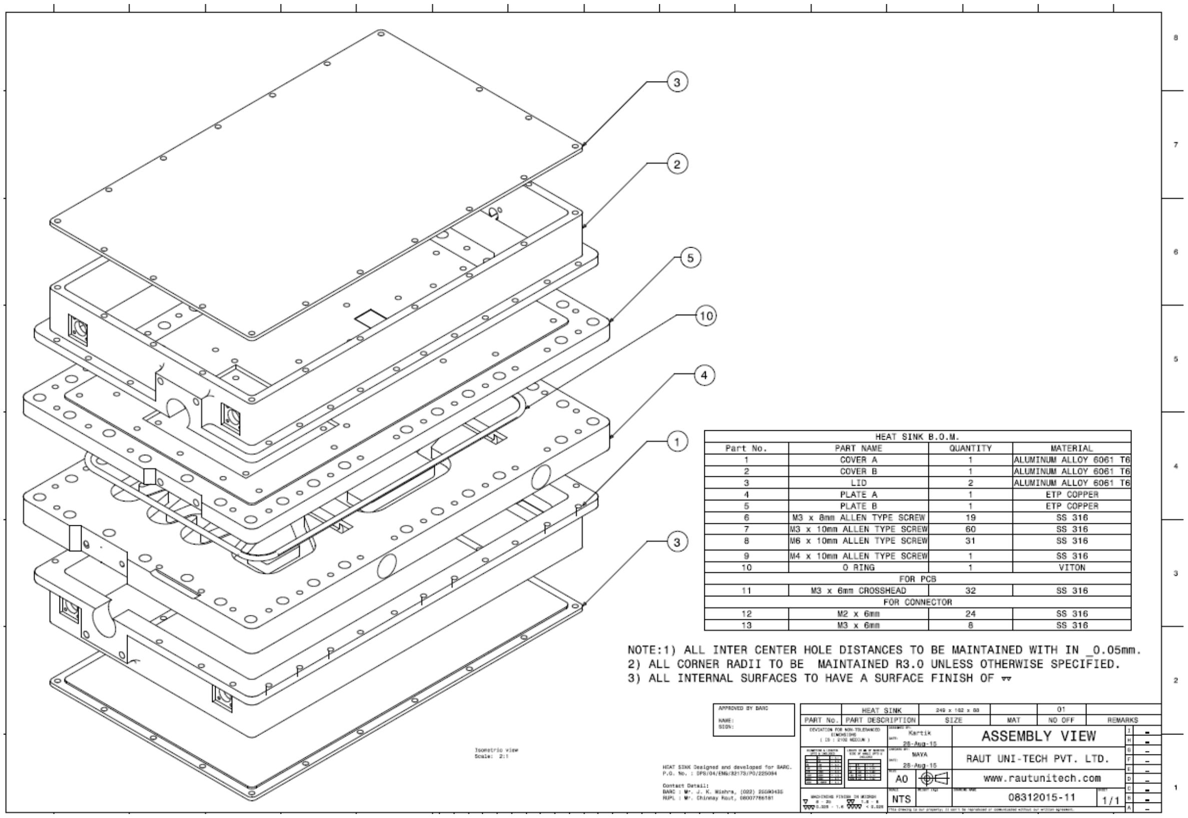


Fig 3 New Heat sink exploded view

These heat plates are joined back to back with enclosures shown in figure 3 to complete the heat sink assembly. A 3D view of the 19” rack for 7 kW, 325 MHz RFPA has been shown in Figure 4.

Amplifier architecture is shown in Block diagram representation in Figure5. It describes the signal flow, interconnection details within the amplifier sub-systems, interface with external systems etc.

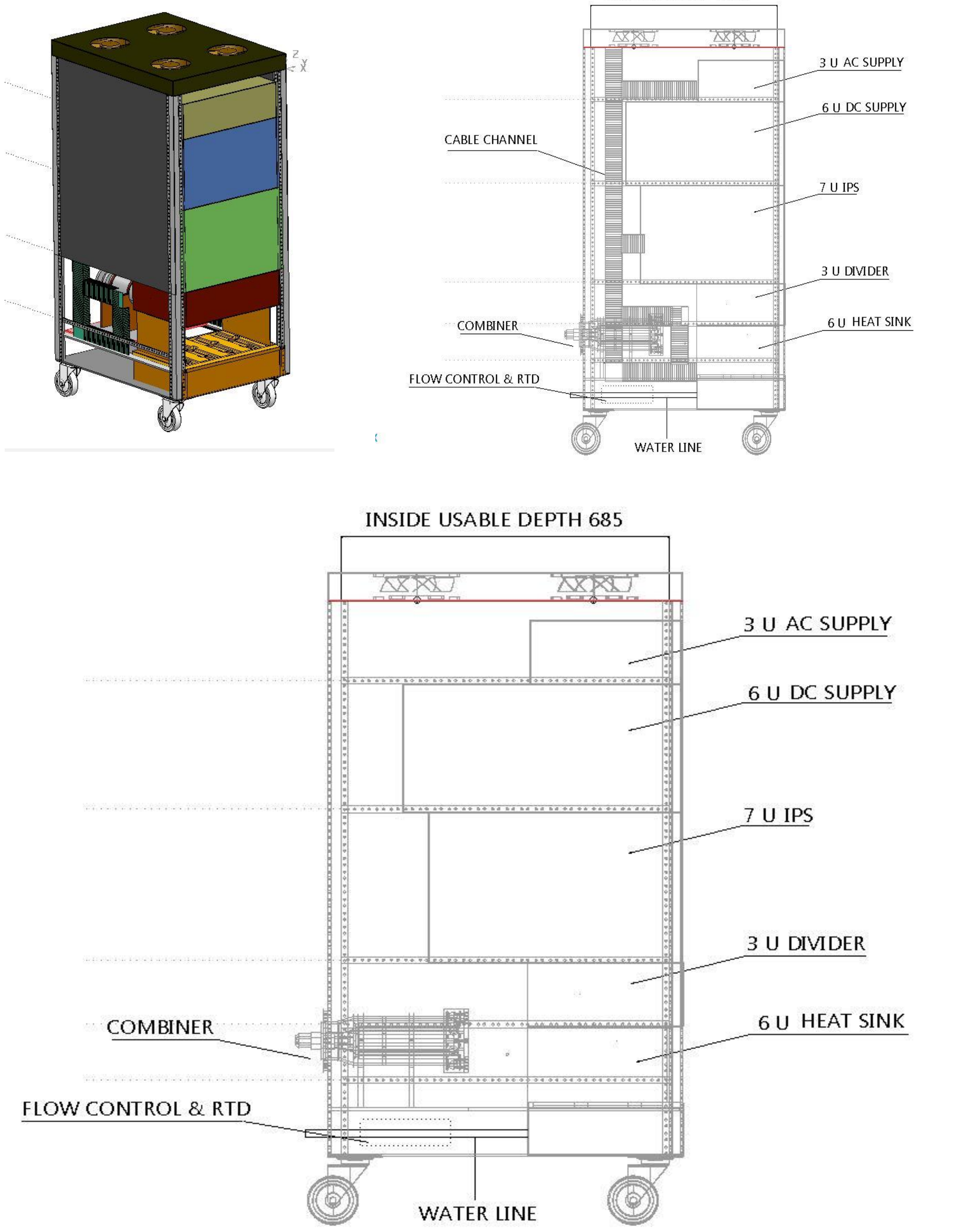


Figure 4Views of the new Prototype rack for 7 kW RFPA

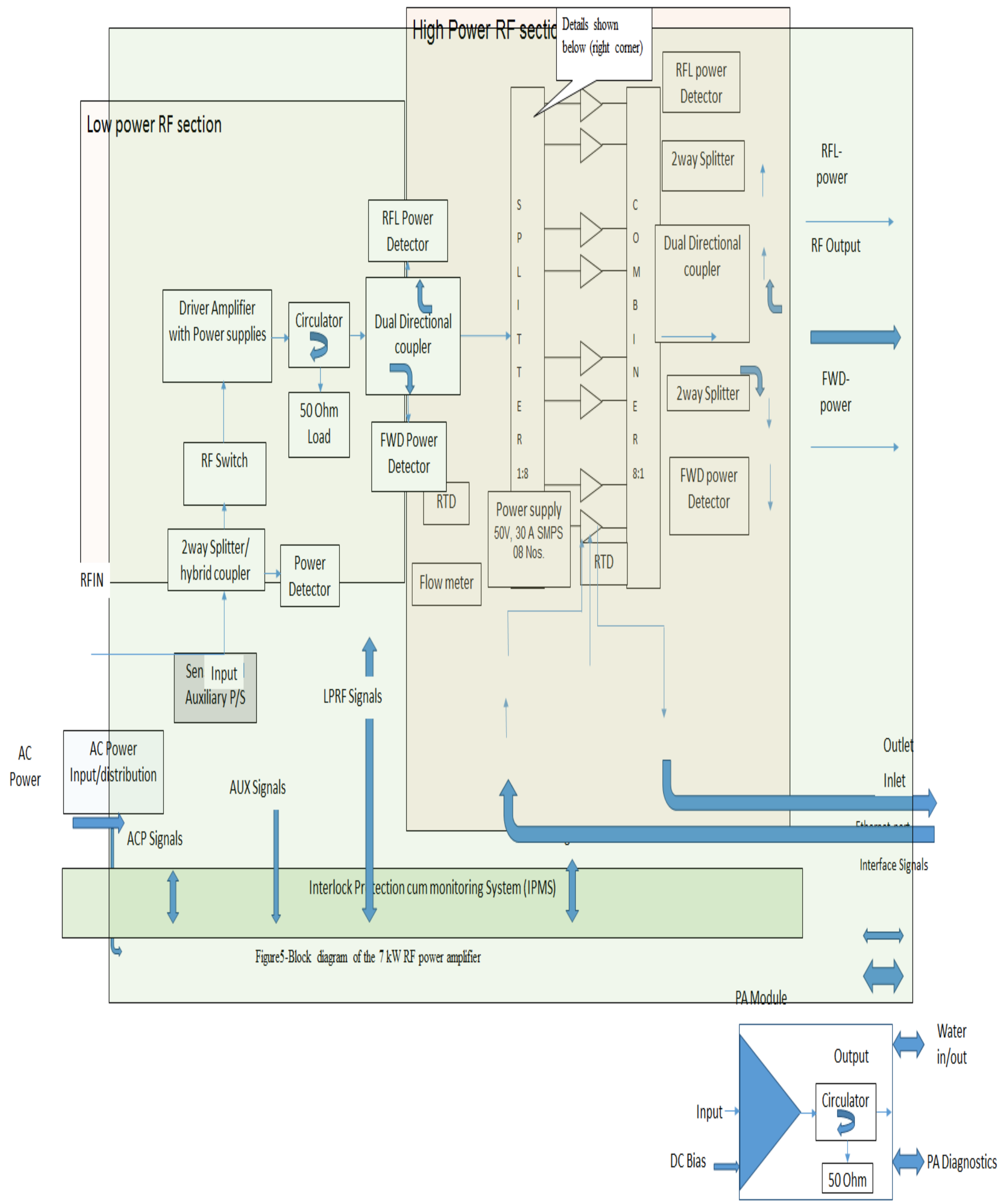


Figure5 - Block diagram of the 7 kW RF power amplifier

5. Specification of 7 KW, 325 MHz amplifier

Amplifier architecture has been described in the block diagram (Figure 5). Basic amplifier modules (1kW) are combined using Wilkinson power combiner/dividers, cooled by the water-cooling system and protected using IPMS. Wilkinson combiner/divider used in the current design of the amplifier does not use internal resistor for isolation. Combiner isolation without internal resistors for combiner designed for 7 kW PA is better than 15 dB. Amplifier modules are protected from reflected power using built in circulators. The complete amplifier is protected from reflected power from the external circulator provided by Fermilab. Internal protection mechanism of the amplifier will protect the amplifier from internal faults/interlocks as well as respond to external faults/interlocks and control commands. Detailed amplifier interfaces and specifications are described under three sections as follows.

A. Description of hardwired Interface Signals

1. **ON/OFF (start)**: This signal is required to soft start amplifier. This signal is generated external to RFPA either generated by control system during Remote mode or manually from RFPA front panel interface in local mode. In response to this signal and safety permit OK, RFPA initiates the turn-on process by switching ON contactor and then after some time (say few seconds) all auxiliary power supplies will be turned on. If DC inhibit is OK, it will turn on its bias power supplies and under no internal faults responds by SSA ready signal. This means that RFPA is ready to accept RF input power from LLRF. This signal needs to be active high for at least 10ms to enable system ON/OFF to avoid false ON/OFF. This signal may be designed as hardwired on D connector as command signal or soft signal through Ethernet port.
2. **SSA Inhibit (RF Inhibit)**: This signal breaks the RF connection from LLRF to the RF power amplifier via GaAs switch (internal to RFPA as second component in the RF path after 2 way divider) (High level TTL signal means OK and low level as fault). This is 50-Ohm fast TTL signal with on a BNC (female) on back panel. This signal comes from RFPI and used to switch OFF RFPA when external fault is observed. An indication of inhibit must be displayed on the front panel interface.
3. **Local/remote mode Switch**: Local mode operation of the RFPA is designed for diagnostics and qualification testing, installation and commissioning purposes of RFPA with dummy load or with RF cavity and other accelerator sub systems e.g. RFPI, control system etc. Local/remote mode should be set using locking toggle switch or key switch for safety reasons. In local mode, amplifier is controlled locally using front panel control interface and protected by its internal IPMS and external interlocks i.e. RFPI. In local mode, RF input must be provided by external signal generator or through LLRF system. In local mode, external control system will be able to monitor RFPA parameters but it will not be able to control its operation. In remote mode, RFPA is controlled by control system and RF input will be provided by LLRF. Remote read-back of all parameters will be available in both modes through Ethernet port on RFPA back panel. In remote mode, RFPA is fully integrated with and controlled by control system and RFPI for external interlocks/protection. A high level signal means remote mode operation while low-level

signal means local mode operation. Internal protection system is active in both modes of operation.

4. **SSA Ready/Fault**: This signal is generated in response to ON/OFF (start) signal described above and is active high when amplifier is ready to accept RF input from LLRF This signal goes to RFPI and control system from RFPA back panel. This signal defines the amplifier health and it is high when all the amplifier parameters are within the operating set limits. If amplifier parameters are not healthy then this signal goes low and amplifier is said to be at fault or have internal interlock/fault or DC inhibit (or safety permit) is low (open). This status signal is communicated to control system and front panel interface of RFPA.
5. **SSA RESET**: To reset RFPA fault, after external/internal fault is removed. This signal needs to remain at high level for minimum of at least 100ms for assertion of reset. Reset can also be performed from front panel in local mode. Reset can be performed via Ethernet port as well.
6. **Gating/timing signal:** This signal comes from control system as a trigger for data acquisition. The actual data acquisition can be done relative to the rising edge of this pulse after a delay which is specified by the control system over Ethernet. The gate signal will be an active high 50 Ohm drive TTL signal with a minimum pulse width of 100 nanoseconds. This signal could be similar to the video pulse used in old generation system. RF pulse widths as short at 100 microseconds can be used when conditioning the cavities. Nominal RF pulse width is 6 msec for PIP-II. The history feature of the amplifier control must data log and time stamp any state changes. This timing gate comes from the accelerator timing/clock system and will synchronize the gating for pulsed operation.
7. **SSA_ALRT**: SSA_ALRT is a soft warning signal, which indicates that RFPA is operating under some constraints and is operating under de-rated mode of operation. Examples of warning conditions are water temperature above 28+/- 2 degree C or ambient temperature 25 +/- 10 degree C or one RF modules in the amplifier is not healthy. This signal is communicated through Ethernet port to control system.
8. **A DC inhibit signal will be provided by the RFPI system**. This is a TTL, 50 ohm to ground input and will be active HIGH. i.e. high indicated OK, low or disconnected cable means not OK. This signal will be available on BNC connector.
9. **A safety permit input will be a contact signal** or equivalent. A closure indicates OK, while disconnected cable or open indicates NOT OK. This signal comes from the external safety interlock system. Conditions for this signal being open may be that the tunnel is not secured or other safety conditions are violated. If contact signal is open, RF switch, DC power and AC power to the SSPA will be removed one by one in this sequence. This signal will be available on D-sub connector.

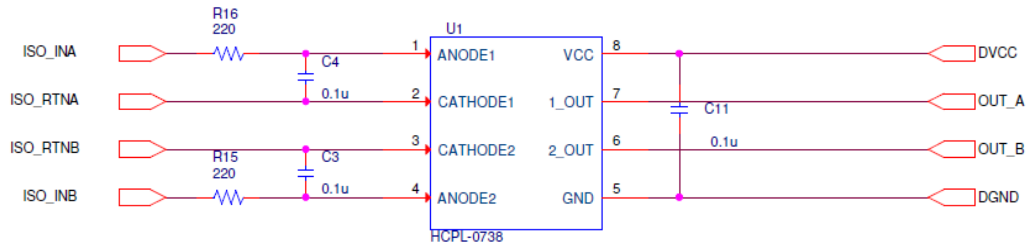
Details of the interface signals

a. Control input to RFPA

All the inputs to RFPA are optically isolated and are having a 50 Ohms termination. The system can support different voltage levels signals by adding appropriate series resistance. The default signal level is 5V TTL Active high mode with 50Ohms termination.
The reference schematic is shown in fig 6.a

b. Status output from the PA

All the outputs from RFPA are optically isolated and are having a 50 Ohms drive. The system can support different voltage levels signals by changing the default DC/DC converter provided isolated output voltage. The default signal level is 5V TTL Active high mode with 50Ohms drive. The reference schematic is shown in fig.6b



Optoisolator output is active low.

Fig.6a: The optical Isolation section at input as well as output side

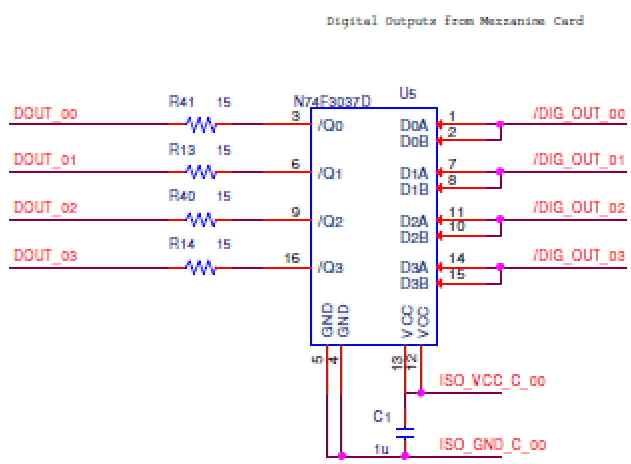


Fig.6b: The 50 Ohms cable drive at the output of Optical isolation section

Ethernet port: All the Amplifier operating point parameters, status signals will be available to external systems via Ethernet port. Amplifier data can be read back and written to externally. Control system (of FNAL) controls the amplifier operation via this port under remote mode of operation.

Remote interface

Remote access to the amplifier is via Ethernet port using Modbus, TCP, or EPICS protocol, and through the D-connector. A functional overview of the interface is shown below in fig. 7

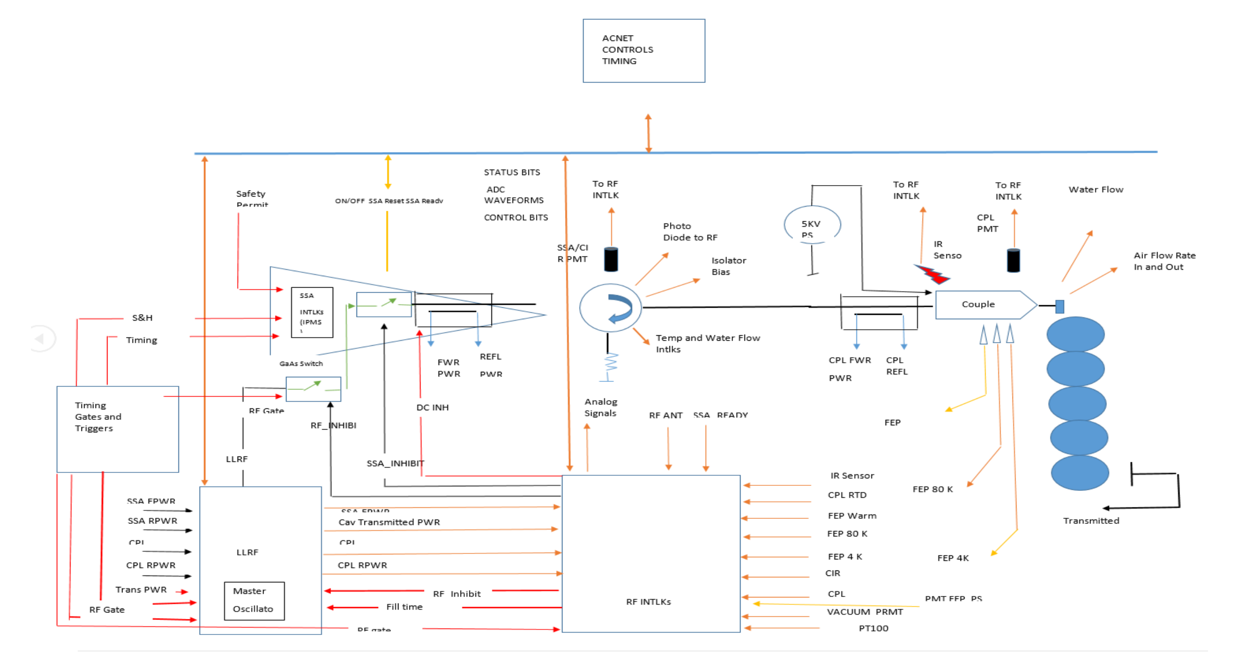


Figure 7 Block diagram of interfaces

Table 1: Technical specifications of 7 KW, 325 MHz amplifiers		
B. Electrical specifications:		
Item	**Parameter**	**Value/range**
1	RF output (kW), CW and pulse	0-7.0kW Minimum pulse width of 100 microseconds, Maximum pulse width 10milliseconds,maximum 20 Hz repetition rate
2	Centre Frequency (MHz)	325
3	1 dB Bandwidth (MHz)	5 MHz or +/- 2.5 MHz minimum
4	Power gain (dB)	62-68
5	1. DC to RF Efficiency (at 7 kW) 2. AC to RF efficiency	65% ~ 55%
6	1 dB compression power (kW)	≥7.0 kW
7	Group delay	< 100 ns
8	Gain magnitude variation in 10 dB dynamic range (10% to 100% of full rated power)	< 3 dB (amplifier is in class AB bias near to class B, gain increases first from very low gain to maximum then decreases resulting in 1 dB compression point)

9	Amplifier phase variation in 10 dB dynamic range	$\leq 15^{o}$
10	Temperature coefficient of gain magnitude and phase (from 23 ^{o}C to 33 degree C temperature range)	≤ 0.02 dB/^{o}C and $\leq 0.3^{o}/^{o}$C
11	Noise Figure:	20 dB max
12	All Harmonics (dBc)	<-25dBc
13	Spurious (dBc)	< -60 dBc@ 60 Hz and < -80 dBc @ 100 kHz
14	RF output port	50 Ohm, 3 1/8" EIA flange on rear panel
15	RF input	50 Ohm, N connector (F) on rear panel, input return loss <-15 dB minimum
16	AC input power to the 7 kW amplifier unit	3 phase 4 wire (Delta with ground), 480 VAC, 60 Hz, 32 amp breakers, 14 kW of AC power (Max) at 7 kW RF output power.
17	AC Power distribution panel	1. AC power input to the amplifier on the back panel of the amplifier. 2. AC power input on an internal terminal block. Power cable to be provided by Fermilab. Appropriate grommet hole for the conductor needs to be specified. 3. AC power will be connected to three phase main circuit breaker (MCB). Internal fusing is also required for each DC power supply and ancillary power circuits.
18	Parameter monitoring, logging and display Remote and local mode of operation using Front panel control/switch	1. Bias voltage and current, forward and reverse power, temperature of MOSFET for each 1 kW amplifier module and driver PA 2. Forward and reverse power at divider input and combiner output. 3. Water flow rate, inlet and outlet water temperatures, rack temperature at critical place, fan fail protection, i.e. monitoring that fan is functioning. 4. Input AC power sense indicator.
	Interlock and protection is implemented for Fast protection as well as slow protection using VME64x based controller. FPGA design with mezzanine card approach	1. Excessive VSWR (>1.4:1) at output/input, water inlet/outlet temperature, water flow rate (less than 32 lpm), low/high ambient temperature range. Adjustable trip levels by end user within design set limits.

	is utilized to implement the Analog and digital signals for monitoring and protections.	2. Over/under voltage and over-load of the bias power supplies to PA modules 3. Excessive heat sink temperature (to be set by BARC design based on input water temperature of 28 C nominal). 4. Amplifier trip if more than one amplifier module fails with remote and local indication. 5. RF overdrive protection @ approximately 0dBm.
19	Interface signals, more details can be seen in the next section	RFPI system is using 50-ohm TTL signals that are not optically coupled, as these signals require fast operation. Optical isolation will reduce the response time.
	1. SSA-Inhibit- from RFPI to Power amplifier	On BNC connector (back panel) Inhibit is active low such that a disconnected cable will provide a fault.
	2. SSA_Ready/Fault- signal going to RFPI from Power amplifier	On a BNC connector (back panel), active high, it is good option to place this on BNC, as this signal will be going to RFPI, others on D connector are going to control system.
	3. SSA Ready/Fault: From Power amplifier to control system	On a D connection (back panel) active high signal means OK/ready, low signal means fault.
	4. SSA RESET: From control system to Power amplifier	On a D connection (back panel) active high. To reset RFPA fault, after external/internal fault is removed. This will be replicated over Ethernet.
	5. Local/remote mode Switch:	Local mode is used during qualification testing, installation/commissioning and maintenance of the amplifier. This switch is used to select modes and is read back remotely. Local mode will allow amplifier turn on/off, reset, monitoring of faults from the front panel interface. Remote read-back is always enabled in both modes. In remote mode, RFPA will be controlled through the commands from the Fermilab control system and RFPI. Switch should be locking toggle or key switch located on the front panel. This signal will be available on D connector at rear/front panel.
	6. ON/OFF (start):	In response to this signal, RFPA (SSA) will start up by energizing all the sub systems and be ready for RF power input. Read-back of amplifier status should be reported both

		locally and remotely i.e. ready/fault status, forward and reflected power, PA modules status, DC power supply status, local/remote mode etc. D sub connector on front panel, and front panel local interface. This will be replicated over Ethernet.
	7. Pulse/CW mode	Control system will provide this signal to separate the CW and pulse mode operation. CW active high, pulse active low on D connector rear panel. This will be replicated over Ethernet.
	8. Timing/gating signal	Acts as trigger signal and allows synchronized signal sampling for monitoring and protection purposes. 100 ns pulse width active high rear panel BNC.
	9. Safety Signal	A front panel "emergency shutdown" button could be employed at the discretion of BARC/DAE.
	10. **DC inhibit signal**	A DC inhibit signal on BNC will be provided by the RF interlocks. This is a TTL, 50 ohm to ground input and will be active HIGH. i.e. high indicated OK, low or disconnected cable means not OK.
	11. **Safety permit**	**A safety permit input will be a contact closure** or equivalent. A closure indicated OK, disconnected cable or open indicates NOT OK. Signal to come from the safety system.
20	EMI/EMC	1. IEC61204: P/S stabilized low voltage at CW operation 2. IEC61204-3: Emission 3. IEC-61204-4 Immunity 4. IEC-61010-1 safety rules for the electric appliances of measurement regulations and laboratory
21	Interface ports	Ethernet, RS-485, USB etc. rear panel
22	Communication protocol	Mod-BUS/TCP or EPICS base
23	1 kW Power amplifier module DC P/S for 1 kW PA modules	DC feed: D-Sub combo connector RF Input connector: QMA connector (F) Output connector: 7/16" DIN Maximum power output-1 kW @ 325 MHz Power gain: 21 dB (min) Efficiency: ≥ 68%

		50V, 30A output, efficiency ≥ 89 %@ full load, with fan fail, overvoltage, over load protection. Cooling: Forced air cooled
	Mechanical Specifications	
Item	**Parameter**	**Value**
1	Water cooling header (IN/OUT)	NPT (male) of 1"size
2	Water type	LCW water compatible cooling system
3	Water cooling header material	Copper/SS, interconnecting individual amplifier modules
4	Internal pipes and connections	Flexible rubber hose pipe, with ½" NPT (F) connectors (SS-304 material)
5	Nominal water Inlet Temp Warning range Interlock/fault temperature	28°C within 26-30°C +/- 3 °C to nominal range Outside +23 °C to +33 °C an appropriate integration time needs to be specified to avoid nuisance trips for prompt fluctuations. A few seconds should suffice.
6	Inlet Pressure (Max.)	125 PSI or 9 bar
7	Water flow rate (Min)/minimum pressure difference	32 LPM minimum at 60 psi of minimum pressure differential, operating water flow range will be specified after the final design calculation
8	Heat sink material (water channel)	Copper (ETP grade)
9	Heat sink shielding enclosure	Aluminum
10	Nominal Ambient temp. Warning range Humidity	+15 °C to+ 35 °C +/- 5°C above nominal operating range Any temp. Above outside +10 to +40 is fault/interlock; an appropriate integration time needs to be specified to avoid nuisance trips for prompt fluctuations. A few seconds should suffice. 30-90 % non-condensing
11	Combiner material	Al and Cu
12	Rack air cooling	Fans on the front or back panels of the amplifier with exhaust on the rear panel and standard sized air filters for inlet air on front panels
13	Amplifier rack size	19" Rack, 30 U height (prototype rack under construction at BARC as shown in figure 4), 686 mm (27 inch) usable depth. Footprint for this rack is taken as per the drawing available at Fermilab as in Appendix A (Fermilab rack).

		All external rear panel connectors must fit into this length. 3-1/8" output coax could exceed the depth dimension, as rear doors on the racks will not be used at PXIE.
14	Quality control: Vibration and Shock test for individual sub racks for transportation purpose on a sample basis	**IEC60068-2-27 (Shock):** General test for robustness, handling and transport for land based items **IEC60068-2-64 (Vibration)**
15	Ingress Protection (IP) category	IP20

6. Power Budget and cooling requirements

7 kW RFPA @ 325 MHz for PIP-II SSR1 cavities uses both water cooling and forced air cooling as thermal management strategy for its operation.

Water cooling requirement specifications for the amplifier are

1. Nominal operating temperature range for inlet water: +28 +/- 2 ^{0}C
2. Operation under warning mode: Inlet temperature above of +/- 3 ^{0}C outside nominal operating temperature. The amplifier will operate in de-rated mode.
3. Inlet water temperature outside 28 +/- 5 ^{0}C will lead to interlock trip and amplifier will shut itself down.
4. Water flow rate: 32 liters per minute at 60 PSI (min.) differential pressure
5. Water quality: Low Conductivity Water (LCW)

Ambient requirement specifications

1. Operating ambient temperature range: +15 ^{0}C to +35^{0}C
2. Warning range for ambient temperature: 5 ^{0}C outside the operating temperature range
3. Ambient Temperature interlock trip will be generated if temperature goes out of the +10 to +40 ^{o}C.
4. Humidity: 30-90 %, non-condensing type

Power Budget: 7 kW RF Power Amplifier

Assumptions for the power budget calculations

a. DC power supplies efficiency is 89% at full load. These power supplies are air-cooled.
b. DC to RF efficiency of the 1kW amplifier modules is 69% and is water-cooled.
c. DC power to IPMS is 350 W and all the power is going into air.
d. Power lost in the cables and combining process is 5%, which goes into the air.

Power going in the different sub-systems are described below and also presented in graphical format in figure 9.

1. Total output from the 7 kW Amplifier $\mathbf{P_{out}}$**= 7200 W**

2. Total RF power from the modules (Max) P_{RF}= 7600 W
3. Power losses in the cable and combiner dumped in the air (**P1**)[1]= P_{RF} - $\mathbf{P_{out}}$ = **400 W** (Max)
4. Total DC power going in PA modules (P2): 11015 W
5. DC power for Driver PA (P3)=250 W
6. DC power to IPMS and sensor circuit (P4)= 350 W
7. Total AC power to the system@ 89% efficiency $\mathbf{P_{AC}}$**= 13050 W**
8. Total power going into the water (P5) = P2-P_{RF} +P_3 = 11015 W -7600 W +250 W =3465 W
9. Power dumped in the Air from all the PS (**P6)** = P_{AC}- (P2+P3+P4)= **1435 W**
10. Total Power dumped in the air from 7 kW PA P_{air}=P1 + P4+P6 =400+350+1435 = 2185 W

Total heat load to the ambient: P_{air} =2185 W*(The air is to be vented through the rear panel.)

Total heat load to water P5 = 3665 W*

*These values may change by 10% after final qualification tests on the amplifiers as per the new FRS/TRS

[1]Note: Some portion of this power may go to the water as power cables and combiners are connected with PA modules, which is water-cooled.

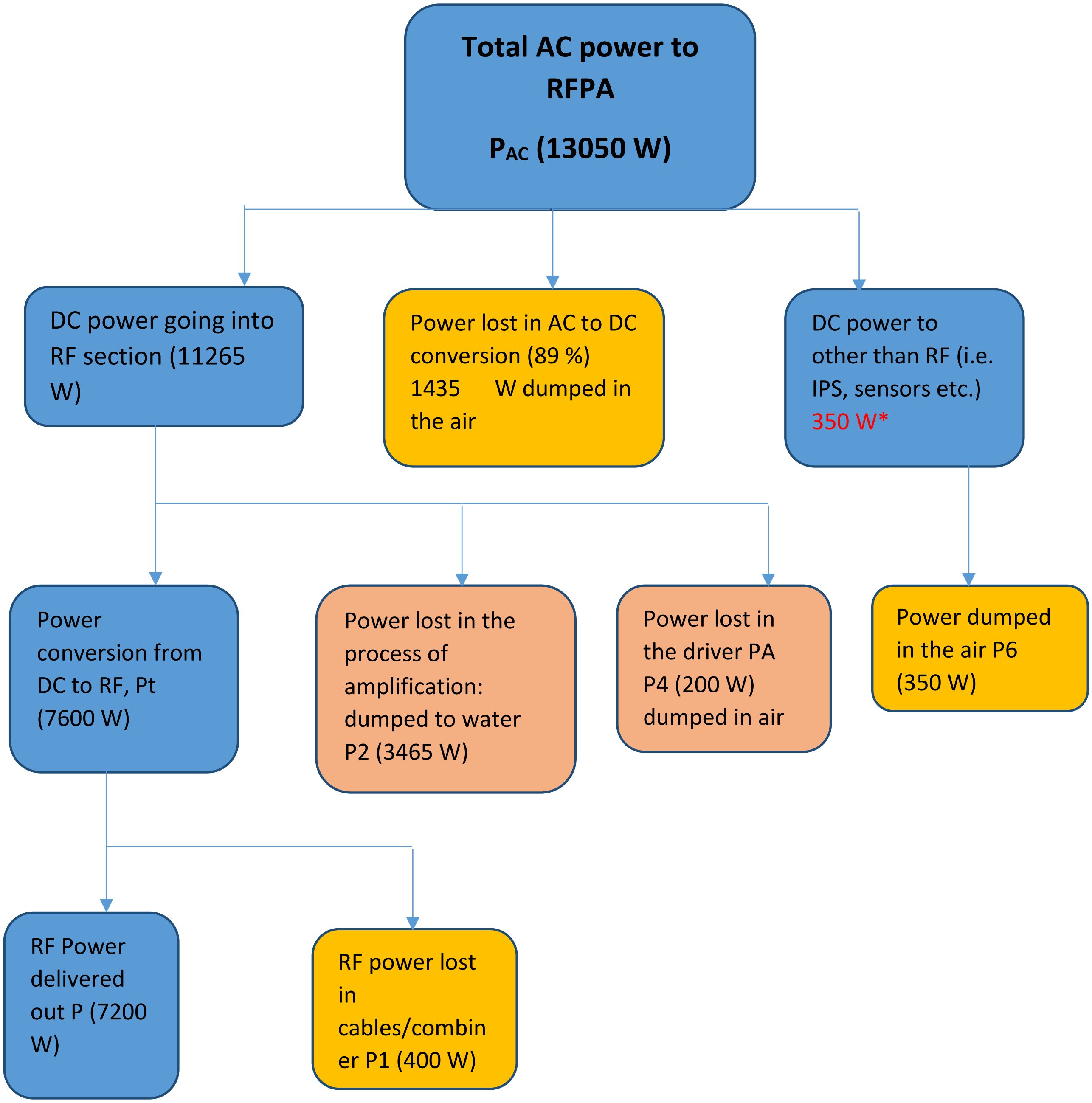


Figure9 Power budget for the 7 kW, 325 MHz, RFPA @ 7.2 kW

7. RF Amplifier operational details

7.1 Startup procedure

Interlock Protection and Monitoring system (IPMS) turns ON when the AC power is connected to the PA. After IPMS system is ON, it starts communicating with the control system over Ethernet as well as start monitoring the hardware interface signal for any command.

I. IPMS receives a startup command based on the following operating modes
   a. If RFPA is in local mode, front panel local control of the amplifier will control and issue ON/OFF command. External control system will not be able to control the operation in this mode but can read the amplifier parameters.
   b. If RFPA is in remote mode, external control system is responsible to send start/stop (ON/OFF) command/signal and control the amplifier operation which IPMS receives over Ethernet.

II. In response to Start-up command from local/remote control system, IPMS of RFPA will check for safety permit signal if it is closed or open. If safety permit contact is closed, contactor in the PA will be closed allowing RFPA to be powered. All the auxiliary P/S in the RF amplifier are switched ON in proper sequence. The RFPA performs internal safety and interlock of itself.

III. Once the DC Inhibit signal is OK (High) PA bias power supplies will be turned ON. The RFPA performs a safety and interlock analysis of itself. If any fault condition is present it drives the SSA Ready/fault signal into fault mode and also informs the control system about it. If all the internal interlock conditions are normal; it drives the SSA Ready/fault signal into ready mode.

7.2 Shut down procedure

I. To shut down, amplifier needs OFF command (without RFPA faults or external faults) from the control systems in remote/local operation or over Ethernet in case of remote mode of operation.

II. Once RFPA is turned off, IPMS system should be turned OFF if AC mains power to the RFPA needs to be turned off. This can be turned OFF via a suitable command over Ethernet. AC mains supply can be turned OFF only when IPMS is turned OFF.

7.3 Internal protection

I. Any fault event in the RFPA will generate a fault/interlock signal to protect itself from damage. Fault event is an event when any one or more amplifier parameter go out of safe operating range or an external fault is detected and removes the permit from the amplifier.

II. This event is communicated via hardwired signal on D connector and Ethernet port to control system and via BNC connectors to RFPI.

III. In response to this fault (event) signal, amplifier will either disconnect only RF input from the amplifier by opening RF switch or disconnect RF as well as shut down DC bias power supplies depending on the type of fault.

IV. The internal protection response time of the protection system is < 10 us for RF signals and 1msec for other signals.

V. External SSA inhibit and DC inhibit signal goes to RF switch control pin via a gate to implement fast protection. DC inhibit signal going low turns OFF DC power supplies too.
VI. Safe operating range for the amplifier parameters is divided into operating range, warning range. Parameter value beyond this range causes generation of fault/interlock.
VII. In operating range, amplifier will work as per the specifications
VIII. In warning range, amplifier will operate in de-rated mode. De-rated mode of operation means, PA will operate at 60% of full power (7 kW), reducing the stress on the components. Once warning signal is generated, LLRF should reduce the RFPA output to 60% of full power (7 kW).
IX. If any parameter goes out of safe operating range (means fault has happened), the amplifier will go in protection mode and generate fault/interlock, changes its status to 'not ready', sends this information to control system, front panel interface, and shut RF OFF/DC bias OFF. These operating limits are listed in a file and are available to control system through Ethernet port for read/write purpose.
X. After rectifying the fault/interlock, RF amplifier can be reset through 'RESET' signal to the PA either remotely or locally depending on the control state of the amplifier.

7.4 External protection

I. Amplifier accepts fast RF OFF/ON hard-wired signals (SSA_INHIBIT and DC_INH) from the external system (RFPI) to enable RF ON or OFF, on BNC (F) connector on rear panel.
II. Only RF is inhibited (OFF) by external SSA_INHIBIT signal, SSA will be in Ready mode. This signal makes or breaks RF path using RF switch at the amplifier input.
III. Both RF and DC will be turned OFF in response to DC_INH and amplifier turns its status as not ready. Amplifier will recover from this state only when DC_INH signal made high again and unit is RESET.
IV. If repetitive fault conditions are observed which are deemed critical by RFPI it drives RF_Inhibit, SSA_Inhibit and DC_Inhibit low. IPMS will respond to these signal mentioned in detailed under "hardwired interface signals". This is a very rare event but is essential to protect the SSRA (what is SSRA? Do you mean RFPA?).
V. If a water flow fault is detected, full shut down of the amplifier will occur using water flow meter inside the RFPA and included in internal protection. Total water outlet flow need monitoring.
VI. Safety permit signal going open will cause complete shutdown of the SSA. This will be done in a sequence of RF OFF, DC power OFF and then AC power OFF.
VII. In response the SSA inhibit signal from RFPI, the Ga-As switch inside the SSA (RFPA) will be closed thereby permitting the RF power from LLRF to drive RFPA.
VIII. In case, an external fault condition is observed by RFPI it removes the permit to Ga-As switch by lowering RF_Inhibit and SSA_Inhibit signals.
IX. When the fault is cleared, the operator (control system) will reset the RFPA and (or) RFPI can permit the operation by driving all the suitable signals to high state.

7.5 Data logging and fault diagnosis

I. All the internal parameters of the amplifier are monitored and logged inside the internal memory. Slow signals are logged at 100 Hz rate, the fast signals are logged at 10 kHz. A time and date stamp will be recorded for each change of state or fault condition.

II. 1000 points of the signals will be stored in a cyclic memory. Under fault condition, the parameter values before and after the fault event will be stored in the memory for diagnostics purpose.

8. Acceptance test procedures

8.1 Documentation

Documentation of 7 kW RF power amplifier will involve

1. Drawings/schematics of all the individual components and circuits
2. Electrical wiring/interconnection diagram for the 7 kW amplifier
3. Bill of material (BOM) for 7 kW power amplifier
4. All the test reports to establish specifications of this document
5. Qualification test reports

8.2 Test Procedure for 1 kW Power Amplifier Module:

a. **Physical inspection, Water leak tests**: This includes visual inspection, heat sink modules are tested for maximum hydro pressure tests (max. 150 psi), flow rate (> 10 lpm) measurement testing at 60-psi pressure differential. After passing this test heat sink sample goes for assembly of electronics components on it.

b. **RF cold test**: This test includes measurement of magnitude &Phase of S21, magnitude of S11 and impedance using Vector Network Analyzer (VNA) under no DC bias. This test establishes the electrical integrity of the PA assembly at low power if parameters values matches with the template for these parameters.

c. **Hot test (RF power test)**: This includes measurement of entire amplifier parameter as per the standard test procedures and meet specification listed above. Amplifier power gain, power sweep check for linearity, efficiency, phase response, input return loss, device case temperature vs. power output. These tests are performed over extreme operating conditions for ambient and water inlet temperatures and flow conditions specified in the table 1. Power gain magnitude, phase, harmonics, spurious noise, group delay etc. are measured for their stability and drifts. These tests are done for CW mode of operation.

d. **CW and Pulse test**: In pulse mode, RF input to the amplifier is pulsed and the response of the RF system is monitored. Pulse response parameters like propagation delay, rise time, fall time, etc. are measured. In CW mode of operation amplifier hot test results are valid.

8.3 Testing of passive RF sub-system

a. Passive RF components are tested using VNA for their functional specifications.

b. Power test is done on sample basis to establish power rating.

8.4 Testing on DC power supplies

a. Testing of DC power supply for specifications suitable to FRS needs, i.e. regulation, ripples, efficiency, power factor etc.
b. Endurance testing on sample basis to establish long-term performance.

8.5 Tests on water system

a. Testing of water circuit for maximum pressure of 150 psi
b. Measurement of flow rate under minimum pressure differential of 60 psi to see minimum flow rate requirements.

Testing and calibration of all types of sensors used in the amplifier

8.6 Integration and testing 7 kW, 325 MHz amplifier

1. Measurement of all the parameters listed in table 1 under extreme operating conditions on sample basis.
2. Standard burn-in test (168 hrs.) on amplifier (on sample basis) is done to test its operational endurance.
3. AC to RF efficiency for the complete amplifier.

All the above tests will be documented and marked as traveler document with the amplifier.

9. Quality assurance procedures

Quality assurance procedure is very important document that ensures production quality. To maintain the quality of production following steps will be incorporated for the production process

1. Inspection of the raw material and components, rejection and replacement,
2. Appropriate Storage
3. Physical inspection at every stage of sub systems assembly
4. Environmental testing
5. Physical and electrical testing for quality check after environmental tests
6. Qualification of one 7 kW system for vibration.
7. Burn in tests: 168 hours at room temperature or 48 hrs. at +35 degree C ambient temperature
8. EMI/EMC qualification as per the standards in table 1
9. Functional testing after all the qualification tests
10. Full test of remote control and read-back.

10. Applicable standards

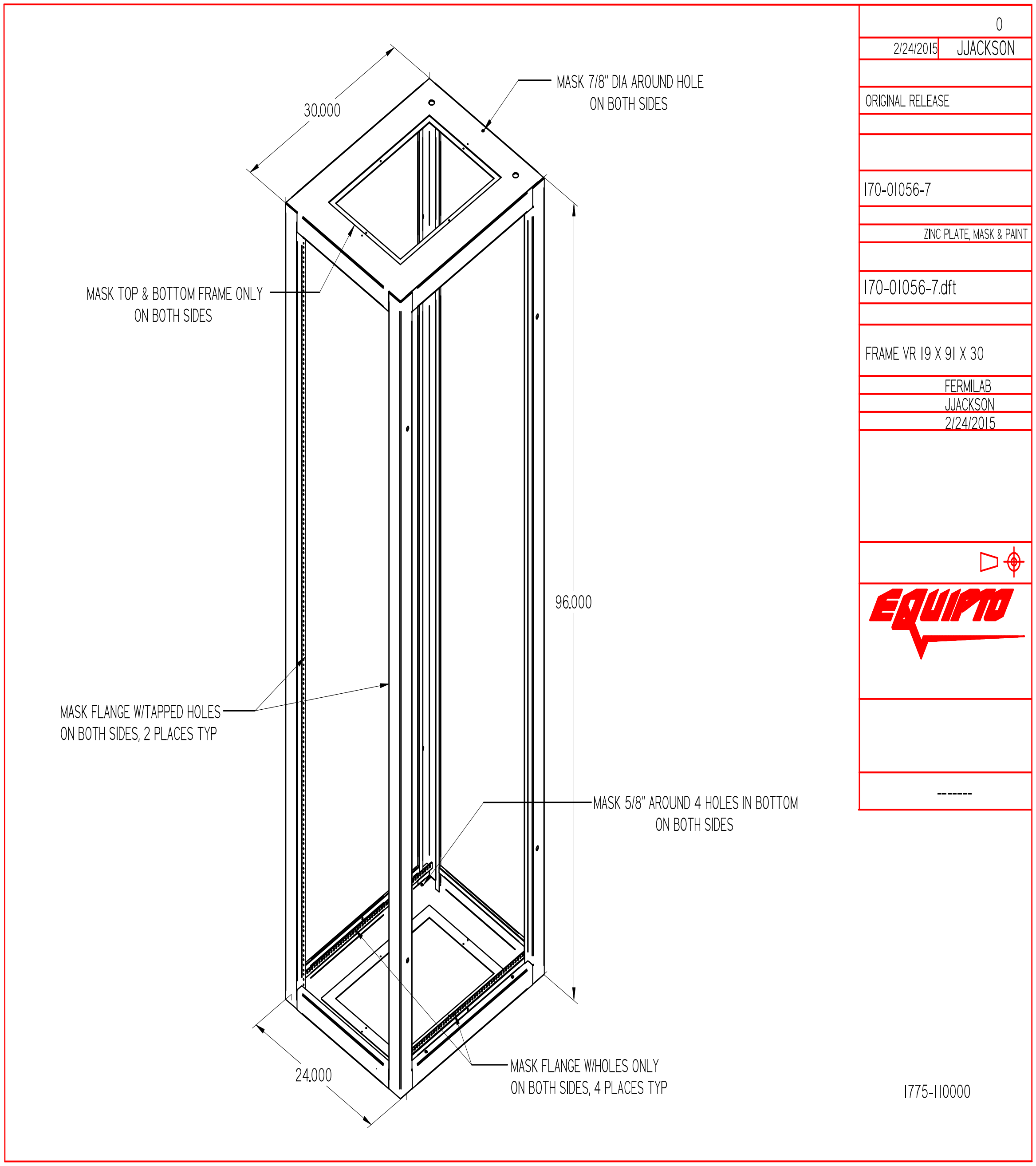
1. Workmanship: IPC-A-610E
2. Standards for PCBs: Lead free, IPC-A-600
3. Environmental standards: ROHS Compliant
4. EMI/EMC standards: IEC-61204-3 &4; IEC61010-1 (safety rules)
5. Vibration standards for transportation only: IEC-61068-27 & 64

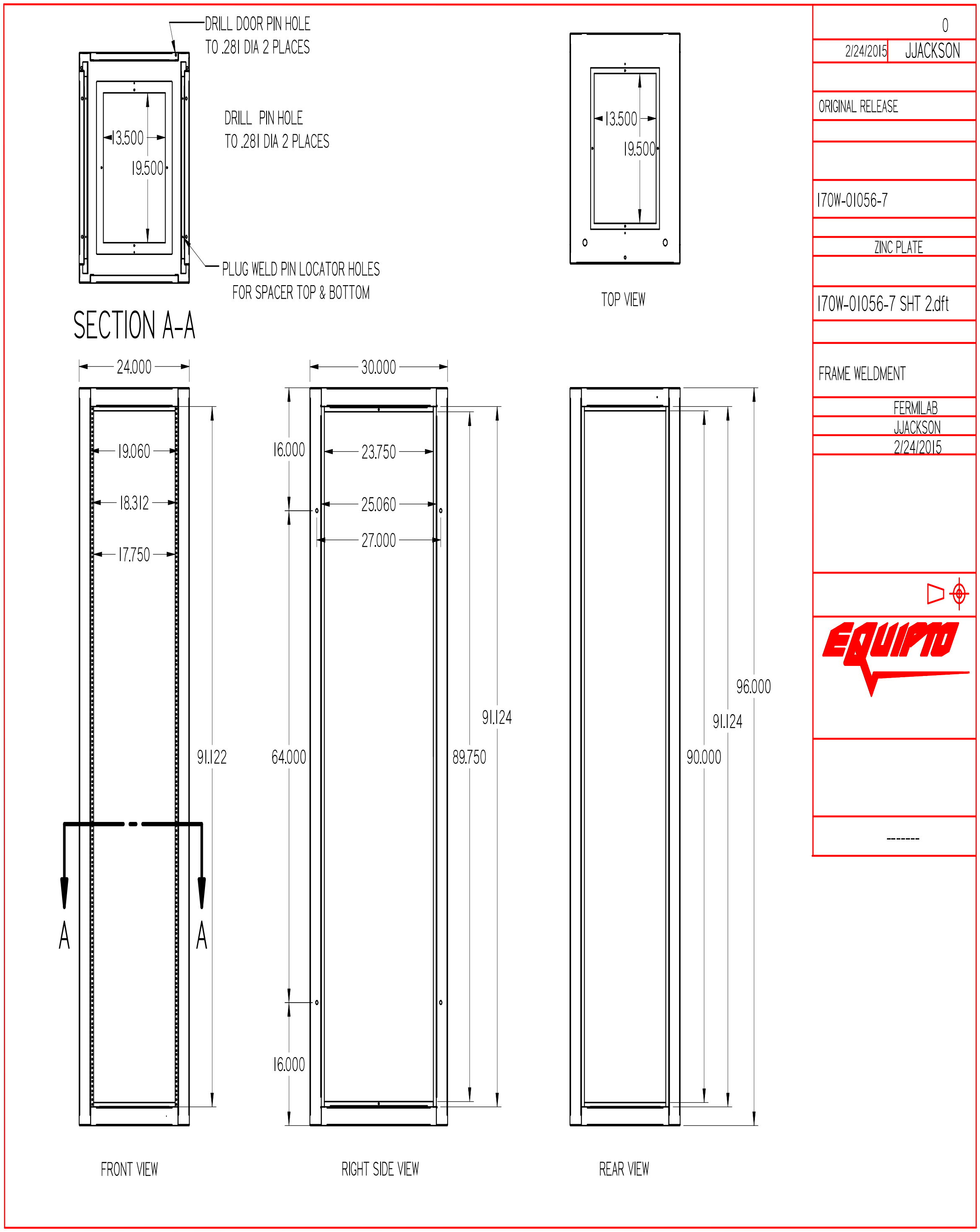
11. References

1. J K Mishra et al, A compact high efficiency 8 kW 325 MHz power amplifier for accelerator applications; 11/2014; 764:247–256; DOI:10.1016/j.nima.2014.05.125.
2. B V Ramarao, Development of 3 kW at 325 MHz solid-state RF power amplifier using four power amplifier modules, 01/2014; 735:283–290; DOI:10.1016/j.nima.2013.09.053
3. Ralph Pasquinelli, J K Mishra, FRS for 7 kW, 325 MHz RF power amplifiers for SSR1 cavities- ED0003408, Fermilab Teamcenter document ED0003408.
4. IEC StandardsIEC-61204-3 &4; IEC61010-1 (safety rules) and IEC-61068-27 & 64
5. The PIP-II Reference Design Report (RDR) Version 1.0 June 2015, Fermilab

Appendix A

Rack drawing available at Fermilab CMTF

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