



 

Department of Atomic Energy (DAE)

Government of India

Anushakti Bhavan, Mumbai 400 001

INDIA

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Fermi National Accelerator Laboratory

P.O. Box 500, Kirk Road & Pine Street

Batavia, Illinois 60510-5011

USA

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**Technical Requirement Specifications**

**for**

**40 kW, 650 MHz Solid State RF Power Amplifier System**

**Rev. 5 (18-May-2020)**

**IIFC Approvals**

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| --- |
| **Prepared by** |
| Akhilesh Jain | Email | Date |  | James Steimel | Email  | Date30 Nov 2017 |
| **Reviewed by (Sub-Project Coordinators)** |
| Mahendra Lad | Email | Date |  | Dave Peterson | Email | Date |
| **Approved by (Technical Coordinators)** |
|  |  | Date |  |  | Email  | Date |

**PIP-II Project Approvals**

|  |  |  |  |
| --- | --- | --- | --- |
| Reviewed by: | FNAL | email | See Teamcenter e-signature |
| Reviewed by: | FNAL | email | See Teamcenter e-signature |
| Reviewed by: | FNAL | email | See Teamcenter e-signature |
| Approved by: | FNAL | email | See Teamcenter e-signature |
| Approved by: | FNAL | email | See Teamcenter e-signature |
| Approved by: | FNAL | email | See Teamcenter e-signature |
| Approved by: | FNAL | email | See Teamcenter e-signature |
| Approved by: | FNAL | email | See Teamcenter e-signature |

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Purpose

The purpose of this document is to list detailed, technical specifications for the proposed design of the 650 MHz RF Solid State Power Amplifier for operating LB650 cryomodules in the PIP-II linac. The information should be sufficient to specify components and services for procurement.

Scope

This document discusses about the technical requirements of 40 kW, 650 MHz RF power amplifier that provides RF power to the LB650 cavities of PIP-II linac. The scope of work includes the design, fabrication, testing and supply of 40 kW 650 MHz Solid State RF Amplifiers.

Acronyms

|  |  |
| --- | --- |
| FESHM | Fermilab ES&H Manual |
| FRCM | Fermilab Radiological Control Manual |
| FRS | Functional Requirements Specification |
| HPRF | High Power Radio Frequency |
| LB650 | Low Beta 650MHz |
| LLRF | Low Level Radio Frequency |
| PIP2IT | Proton Improvement Plan II Injector Test |
| RF | Radio Frequency |
| SRF | Superconducting Radio Frequency |

Reference Documents

|  |  |  |
| --- | --- | --- |
| **#** | **Reference** | **Document #** |
| 1 | RF Power Systems EPDM | ED0002850 |
| 2 | Interface Specification Document for 650MHz SSPA | ED000xxxx |
| 3 | [Fermilab Engineering Manual](http://directorate-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=34) | NA |
| 4 | [Fermilab Environmental Safety and Health Manual](http://eshq.fnal.gov/manuals/feshm/) | NA |
| 5 | Design of 650 MHz, 30 KW Solid State RF Amplifier | NA |
| 6 | System efficiency and performance analysis for high power solid state radio frequency transmitter |  |
| 7 | 650MHz SSPA Functional Requirements |  |

Assumptions

1. The power necessary to operate the LB650 cavities will be generated by combining two, half-power units with a power combiner. Figure 2 shows the configuration of the half-power units and the combiner to give a sense of scale for the size.



Figure : Assembly of 20kW 650MHz Solid State RF Amplifier Units

1. For directional sampling and measurement of high power RF signal coaxial directional couplers are the reliable high-power solution. Coupler structures at different power, designed for present application, are coaxial type with rectangular cross section.
2. PA modules are protected from reflected power using an integral isolator inside the PA modules. However, 40 kW SSRFA, as a complete system, will be protected from the reflected power by employing external circulator at the amplifier output (Provided by Fermilab).
3. Different high power directional couplers will be used to sample RF power at various junctions. Such architecture design allows modularity and scalability to the system.
4. A functional overview and block diagram of different interface signals of 40 kW SSRFA is depicted in Fig. 3.



Figure ‑: Functional diagram of amplifier interfaces

Functional Descriptions

6.1 Interface Signals

**ON/OFF (Start/OFF)**: This signal is required to soft start amplifier. This signal is generated external to SSRFA either by control system during Remote mode or manually from SSRFA front panel interface in local mode. In response to this signal and Safety Permit OK, SSRFA initiates the turn-on process by switching ON contactors 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 SSRFA is ready to accept RF input power from LLRF.

**SSA\_Inhibit**: This signal breaks the RF connection from LLRF to the SSRFA via RF switch (internal to SSRFA). This signal comes from RFPI and used to switch OFF SSRFA when external fault is observed. An indication of inhibit must be displayed on the front panel interface.

**Local/Remote mode switch**: Local mode operation of the SSRFA is designed for diagnostics and qualification testing, installation and commissioning purposes of SSRFA with dummy load or with RF cavity and other accelerator sub systems e.g. RFPI, control system etc. local/remote mode shall be set using key switch on front panel. In local mode, amplifier is controlled locally using front panel control interface and protected by its internal protection interlocks 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 SSRFA parameters but it will not be able to control its operation. In remote mode SSRFA is controlled by external control system and RF input will be provided by LLRF. In remote mode, SSRFA is fully integrated with and controlled by control system and RFPI for external interlocks/protection. Remote read back of all parameters will be available in both modes through Ethernet port on SSRFA back panel. Internal protection system is active in both modes of operation.

**SSA\_Ready/Fault**: This signal is generated in response to ON/OFF signal described above and is active when amplifier is ready to accept RF input from LLRF. This signal goes to RFPI and control system from SSRFA back or top 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 SSRFA.

**Reset**: To reset SSRFA fault, after external/internal fault is removed. Reset can also be performed from front panel in local mode. Reset can be performed via Ethernet port as well.

**Trigger/Gating 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. This timing gate comes from the accelerator timing/clock system and will synchronize the gating for pulsed operation.

**SSA\_Alert**: This is a soft warning signal, which indicates change in some state or that amplifier system is operating under some constraints (operating under de-rated mode of operation). Examples of warning conditions are water temperature above range or one RF modules in the amplifier is not healthy. This signal is communicated through Ethernet port along with being indicated on local panel (with buzzer). This signal is communicated through Ethernet port to control system.

**DC\_Inhibit**: A DC\_Inhibit signal will be provided by the RFPI system. This signal will disable bias to the internal amplifier modules when de-activated.

**Safety Permit**: 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, AC power to the SSRFA will be removed. This signal will be a dedicated input signal.

**Local/Remote read back:** This gives the status about Local or remote operating mode of the amplifier.

Details of DB connector (connected with EIB , Fig. 3)



Fig. 3: DB 25 Connections (Last letter e.g. A, K , E and C represents opto-coupler terminals)

6.2 Operation Sequences

### 6.2.1 Start-up procedure

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

1. Internal IPMS receives a start-up command based on the following operating modes
	1. If SSRFA 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.
	2. If SSRFA is in remote mode, external control system is responsible to send ON/OFF signal and control the amplifier operation which internal IPMS receives from external control system via multi-pin connector located on rear panel.
2. In response to Start-up command from control system, all the auxiliary power supplies in the RF amplifier are switched ON in proper sequence. The SSRFA performs internal safety and interlock of itself.
3. Once the DC\_Inhibit signal is OK (High) PA bias power supplies will be turned ON. The SSRFA performs a safety and interlock analysis of itself. If any fault condition is present it drives the SSA\_Ready/Fault signal into SSA\_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 SSA\_Ready mode.
4. All the internal parameters of the amplifier are monitored and logged inside the internal memory. A time and date stamp will be recorded for each change of state or fault condition.

### 6.2.2 Shut down procedure

1. To shut down, amplifier needs OFF command from the Local Panel Switch in local operation or from remote control system in case of remote mode of operation.
2. Once SSRFA is turned OFF, internal IPMS system shall be turned OFF if AC mains power to the SSRFA needs to be turned off. AC mains supply shall be turned OFF only when internal IPMS is to be turned OFF.
3. IPMS system will perform automated shut down of RFPA and itself if AC mains power interruption is detected.
4. All shut down scenarios (OFF command or AC power interruption) will force the external SSA Ready/Fault signal to “Fault” status.

### 6.2.3 Internal protection

1. Any fault event in the SSRFA 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.
2. This event is communicated via hardwired signal on an external connector and Ethernet port to control system and via SMA connectors to RFPI.
3. In response to this fault (event) signal, amplifier may shut down DC bias power supplies depending on the type of fault.
4. External SSA\_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.
5. Safe operating range for the amplifier parameters is divided into operating range, warning range and overload (fault). Parameter value beyond this range causes generation of fault/interlock.
6. In operating range, amplifier will work as per the specifications.
7. 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 ‘SSA\_Fault’, sends this information to control system, front panel interface, and shut RF OFF and DC bias OFF. These operating limits are readable by control system through Ethernet port. Only expert operator/ service personnel may modify the limits.
8. 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.

### 6.2.4 External protection

1. Only RF is inhibited (OFF) by external SSA\_Inhibit signal, SSRFA will be in SSA\_Ready mode. This signal makes or breaks RF path using RF switch at the amplifier input.
2. Both RF and DC will be turned OFF in response to DC\_INH and amplifier turns its status as SSA\_Fault. Amplifier will recover from this state only when DC\_INH signal made high again and unit is reset and turned ON again.
3. If repetitive fault conditions are observed which are deemed critical by RFPI it drives SSA\_Inhibit and DC\_Inhibit low. Internal IPMS will respond to these signals mentioned in detailed under "Amplifier Interface Signals". This is a very rare event but is essential to protect the SSRFA.
4. If a water flow fault is detected, full shut down of the amplifier will occur, using water flow meter inside the SSRFA and included in internal protection. Total water outlet flow needs monitoring.
5. Safety permit signal going open will open a contactor of the 480 V power supply of the SSRFA.
6. The IPMS will detect interruption in the 480 V power supply and invoke a sequence of RF OFF, DC power OFF and then AC power OFF to ensure that the amplifier powers back on in a safe state.
7. In case, an external fault condition is observed by RFPI it removes the permit to RF switch by lowering RF Inhibit and SSA\_Inhibit signals.
8. When the fault is cleared, the operator (control system) will reset the SSRFA and (or) RFPI can permit the operation by driving all the suitable signals to high state.

 Technical specifications of 40 kW solid state RF amplifier

Table 1: RF Technical specifications of 40 kW solid state RF amplifier

|  |  |  |
| --- | --- | --- |
| **Sr.** | **Parameter** | **Value** |
| 1 | Centre Frequency | 650 MHz |
| 2 | Bandwidth @ 3 dB | ±2 MHz, 4 MHz minimum |
| 3 | Peak power output (typical peak) | 44 kW CW Max |
| 4 | Power output @ 1 dB compression | 40 kW CW Min |
| 5 | Gain | 71 dB minimum, 40 kW output with +1 to +5 dBm drive |
| 6 | Gain Accuracy at Pulse Request | ±5% |
| 7 | Phase Accuracy at Pulse Request | ±3° |
| 8 | Output VSWR Handling | 1.4:1 minimum |
| 9 | Harmonics | -30 dBc Max, tested within 2 GHz bandwidth |
| 10 | Spurious | -60 dBc Max including power supply modulation, tested within 2 GHz bandwidth |
| 11 | Minimum RF Drive Pulse Length | 10 μs Min |
| 12 | Input overdrive protection | +5 to +16 dBm range  |
| 13 | Input impedance | 50 ohms input VSWR 1.4:1 Max,  |
| 14 | Input connector | N type (receptacle) |
| 15 | Output power sampling accuracy | 2% minimum |
| 16 | Output connection | Coaxial 6-1/8” EIA line output.  |
| 17 | Time to replace RF modules or DC power supplies | 3 hours Max |
|  |  |  |
|  |  |  |
|  |  |  |

**15. AC Power:**

|  |  |  |
| --- | --- | --- |
| **Sr** | **Parameter** | **Value** |
| 1 | AC power voltage | 3 wire 480VAC 60 Hz three phase and separate ground, electrical connection at rear top of each 20 kW rack and not interfering with the combiner. |
|  | AC Connection | Internal terminal block / direct on MCCB |
| 2 | Efficiency | AC to RF output 43% minimum at 1 dB compression power |
| 3 | Efficiency at half power | 26% Min |
| 4 | AC Current Pull | 100 A per half-power module Max |
| 5 | Power Factor | 86% Min |

**16. Cooling:**

|  |  |  |
| --- | --- | --- |
| **Sr** | **Parameter** | **Value** |
| 1 | LCW Pressure | 60psi differential(min)125 psi( max) |
| 2 | LCW Temperature-Normal operation. | 28 ± 2 ˚C. |
| 3 | LCW Temperature (Operation under warning mode, de-rated mode) | Outside range 28 ± 3 ˚C (> 25C or 31C<) |
| 4 | LCW Temperature- Interlock trip level | Outside range 28 ± 5 ˚C (> 23C or 33C<) |
| 5 | LCW flow rate | 180 litres per minute.(80-90 lpm per 20 kW amp unit at 60 psi (min.) differential pressure) Max |
| 6 | Water Header | Copper/SS NPT (male) of 1” size |
| 7 | Heat Load to Water | 27 kW per half-power unit Max |

**17. Ambient requirement specifications :**

|  |  |  |
| --- | --- | --- |
| **Sr** | **Parameter** | **Value** |
| 1 | Operating ambient temperature range | +15 ˚C to +35 ˚C |
| 2 | Warning range for ambient temperature | 5 ˚C outside the operating temperature range. |
| 3 | Ambient Temperature interlock trip | 10 C to 40 C.  |
| 4 | Heat Load to Air | 4 kW Max |

**18. Interlock connections :**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Requirement #** | **Name** | **Signal Type** | **Connector** | **Cable** | **Polarity** |
|  | SSA Inhibit | 50Ω TTL | 50Ω SMA | RG-58 | Active Low |
|  | DC Inhibit  | 50Ω TTL | 50Ω SMA | RG-58 | Active Low |
|  | SSA Ready/Fault | 50Ω TTL (50mA drive Max) | 50Ω SMA | RG-58 | Active High |
|  | Trigger/Gate  | 50Ω TTL | 50Ω SMA | RG-58 | Active High |
|  | Safety Permit | Active closed potential free relay contact (input) | 2-pin Phoenix TB | 2-wire twisted pair |  |

**19. Controls connections :**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Requirement #** | **Name** | **Signal Type** | **Connector** | **I/O** | **Polarity** | **Min Hold Time** |
|  | ON/OFF (start) | Opto-isolated 24V (20mA Max) | Standard D | Input | Active High | 200 ms |
|  | SSA Reset | Opto-isolated 24V (20mA Max) | Standard D | Input | Active High | 200 ms |
|  | SSA Ready/Fault | Optocoupler C-E (or D-S) pair (35V & 30mA Max) | Standard D | Output | High=Ready |  |
|  | SSA Alert  | Optocoupler C-E (or D-S) pair (35V & 30mA Max) | Standard D | Output | Active High |  |
|  | Remote/Local | Optocoupler C-E (or D-S) pair (35V & 30mA Max) | Standard D | Output | High=Remote |  |
|  | Pulse/CW | Opto-isolated 24V (20mA Max) | Standard D | Input | High=Pulse |  |

**20. Timing and Communication**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Requirement #** | **Name** | **Signal Type** | **Connector** | **Cable** | **Protocol** |
|  I-ED0006360-H001 | Timing/Gating | 50Ω TTL | 50Ω SMA | RG-58 |  |
|  I-ED0006360-H002 | Communication  |  | RJ45 | Ethernet | MODBUS/TCP |

Quality assurance plan and acceptance test procedure

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. Physical and electrical testing for quality check [4][5]

5. Qualification of one 40 kW system for vibration.

1. IEC60068-2-27 (Shock): General test for robustness, handling and transport for land based items
2. IEC60068-2-64 (Vibration)

6. Burn in tests: 168 hours at room temperature or 48 hrs. at +35 degree C ambient temperature

7. EMI/EMC qualification as per the standards:

1. IEC61204: P/S stabilized low voltage at CW operation
2. IEC61204-3: Emission & Immunity
3. IEC-61010-1 safety rules for the electric appliances of measurement regulations and laboratory.

8. Functional testing after all the qualification tests