

DESIGN STUDY ON A HIGH POWER RF AMPLIFIER FOR THE RFQ *

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Abstract

The RF amplifier of 100 kW (CW) at 165MHz has been studied for a Radio Frequency Quadrupole (RFQ). The RFQ as a linear accelerator will be used for low energy beam section of KBSI accelerator system in order to accelerate and focus the ion beam up to 500keV/u [1]. An RF amplifier is composed of a drive, an intermediate, and a final amplifier stage with power supplies. The intermediate amplifier (IPA) of 5 kW is designed with solid state amplifier modules, and the final amplifier is designed with a tetrode tube. The high voltage power supply for the tetrode provides the fine regulation of 15 kV at 10 A. The RF amplifier is operated by program logic controller (PLC) with interlocks, and a low level RF control for RFQ accelerator. This paper describes the present design study on the 100 kW RF amplifier.

INTRODUCTION

The RF amplifier of 100 kW is composed of a Final Power Amplifier (FPA) of a tetrode TH781, IPA of 5kW with SSPA and a PLC control system. Main component of FPA is a tetrode amplifier: Thales tube TH781 and a resonant input/output cavity TH18781E [2].

Figure 1 shows the block diagram of high power RF amplifier including 6-1/8" coaxial transmission lines such as circulator, loads, directional coupler, and an RFQ.

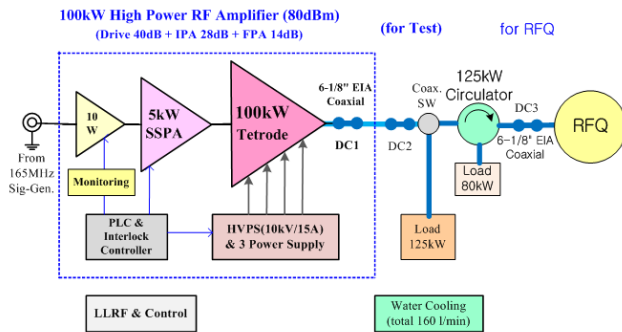


Figure 1: block diagram of RF amplifier for RFQ.

Main power supply is for the anode of 10 kV/15 A to get 100 kW RF output. The others are grids and heater power supplies. The PLC controls the amplifier including power supplies and manages interlocks. Table 1 shows design parameters of the amplifier.

Table 1: Design Parameter of Amplifier for RFQ

Specification	Value	Details
Frequency	165 MHz	Synthesizer
Bandwidth	± 0.8 MHz	-1 dBc
Amp. Stability	$< \pm 0.2$ %	Close loop
Phase Stability	$< \pm 0.2$ degree	Close loop
Operating mode	Continuous	or Pulse mode
Transmission Lines	6-1/8" EIA w/ Circulator	100 kW CW 150 kW peak
Interlock time	less than 2 us	fast, wired

FINAL AMPLIFIER

The final amplifying stage is based on the TH781 tetrode fabricated by Thales. The 100 kW/165 MHz amplifier with vacuum tube has advantages for high power up to 300 kW and cheaper than SSPAs. TH781 is only a tetrode for high power application at 165MHz and has been tested to other projects of IHEP, LANL and IFMIF (International Fusion Materials Irradiation Facility) [3][4][5]. Some power supplies including a high voltage anode supply are needed for operating the tetrode. Table 2 shows specification of power supplies and option items for the FPA of 100 kW RF output.

Table 2: Power supplies and accessories of FPA

Items	Specification	Details
Anode P/S	10kV / 15A	controlled
Screen Grid P/S	1200V / 0.7A	$< \pm 0.1$ %
Control Grid P/S	-350V / 0.9A	$< \pm 0.1$ %
Filament P/S	10V / 375A	DC or AC
Resonant Cavity	Input / Output	TH 18781E
HV Filter	< -50 dBc	Option
Radiation Shielding	X-ray $< 5\mu$ sv/h RF < 0.1 mW/cm ²	Option

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There are some integration parameters: mainly TH781 with a TH18781E as well as option items such as a HV filter and shielding cabinet TH18781E is the resonant cavities of input matching with 1-5/8" coaxial and output cavity matching with 6-1/8" coaxial connector. Therefore, tube connection and matching at 165 MHz of operating frequency can be very easily implemented, and safely operated. Water cooling is adopted for anode and grids, and air cooling supplies for the heater and cavities. The shielding cabinet is to protect any radiations which are less than 5 $\mu\text{Sv/h}$ of X-ray and 0.1 mW/cm^2 of RF from the tube by collision of electrons at anode. Also, integration parameters of tube amplifier for a high power are shown in figure 2. And a support will be designed for tube connection including shielding blocks, and casters which can be moved and adjusted the height of output connection to 6-1/8" coaxial for easy installation.

Integration parameters

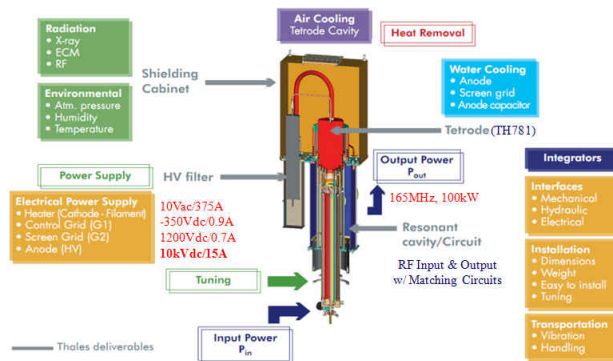


Figure 2: Integration parameter of tube amplifier.

HIGH VOLTAGE SUPPLY

Major anode power supply should provide a high voltage of 10 kV, 15 A. Two types of high voltage supply are mainly liner regulation and switched mode. Linear mode power supply is simple with HV transformer, capacitor, inductor and diode modules. Switched mode is that AC mains input is directly rectified and then filtered to obtain a HV DC voltage. The resulting DC voltage is then switched on and off at a high frequency by electronic switching circuitry. HVPS should include safety features such as current limiting or a crowbar circuit to protect the device by interlock. Any type of power supplies is possible with fine regulation for the anode voltage of tetrode. But the switched mode has some advantages for controls, regulations even more expensive prices than linear type. The HVPS is designed with linear type at first because of economic limitation, and then finally decided to Switching Mode Power Supply (SMPS) type for more accuracy, stability and applicability with developed a Capacitor Charged Power Supply (CCPS) application. The CCPS was developed for a pulse power supply such as modulators for Linac klystron. Therefore, some modifications to CW application as a DC power supply are required for stable operation of the RF amplifier.

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IPA AND DRIVE AMPLIFIER

Intermediate Power Amplifier (IPA) is for driving the FPA as an input up to 5 kW. IPA is designed with Solid State Power Amplifier (SSPA) with LDMOS modules which are 800 W output each because of availability, durability and future possibilities. Power combiners should be designed with low loss, excellent amplitude and phase balance with high power handling capability. Two 4-way combiners or an 8-way combiner is needed to combine to 5 kW power from eight 800 W modules including transmission losses. As total output power is within 5 kW with 1-5/8" EIA flange to connect to input connector of FPA. Radial type combiner structure of 8-way input with N connection is a proper candidate for the IPA. Also as an input of the IPA, a drive amplifier stage of 10 W is essential to control, monitor and interlock the RF power at local mode during only amplifier operation without control system. Figure 3 shows the block diagram of SSPA with combiners.

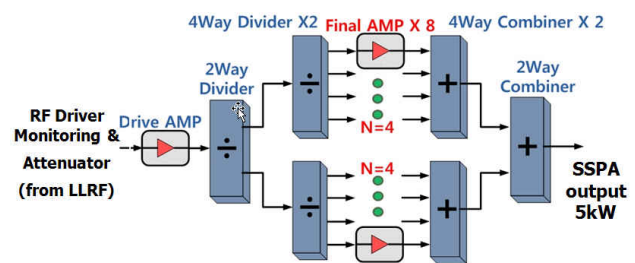


Figure 3: Block diagram of 5 kW SSPA.

PLC CONTROL SYSTEM

The amplifier control system is based on the Yokogawa FA-M3 PLC which will control and monitor all amplifier parameters sequentially with a program. The PLC will operate the amplifier step by step procedure of cooling, filament, control grid, anode and screen grid power supply. In case of any abnormal operation of equipments I/O interlock signals should be switched off the power supplies or RF driver to initiate the appropriate shut-down procedure to avoid any damage to the amplifier and personnel. The Yokogawa PLC is easy to access to Ethernet with a communication module. The operation data of amplifier system as well as RFQ are controlled and monitored with EPICS IOCs remotely. Also OPI control screen is prepared for easy operation, monitoring and fault reset at a beam operation desk.

LOW LEVEL RF CONTROL SYSTEM

The Low Level RF (LLRF) control system is to control and stabilize amplitude and phase of the RF power from amplifier to RFQ. LLRF system is designed with IQ digital technology based on FPGA. The LLRF system provides an RF field control, diagnostic for RFQ for stable operation within $\pm 0.2\%$ (rms) of amplitude and $\pm 0.2^\circ$ (rms) of phase by IQ feedback control loops. The LLRF system also includes some interlocks, local control,

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GUI, and EPICS which can control remotely through Ethernet. Figure 4 shows the block diagram of a designed example of LLRF system.

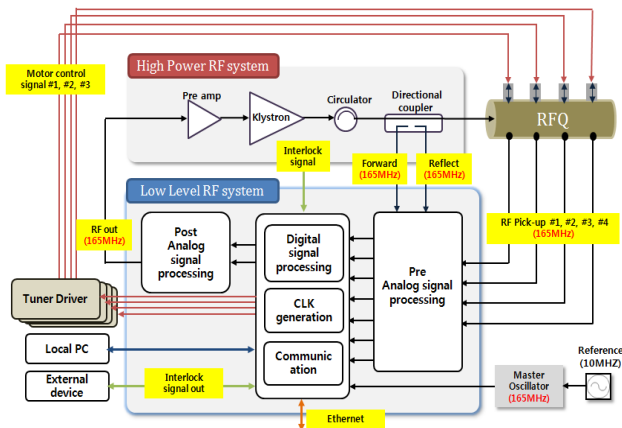


Figure 4: Block diagram of LLRF.

INTERLOCK SYSTEM

The amplifier interlock system has to protect the SSPA and FPA tubes from damage caused by over-voltages or over-currents or arcs inside of vacuum tube. The interlock system has to protect the amplifier at any operation mode as conditioning, local and remote with RFQ and transmission lines. The interlock system is very important for safety operation and should be considered for a redundancy if possible. The main interlocks of the amplifier are the following [6]:

- Anode interlock: Interlocks from over-voltage and current have to be very reliable. In case of an arc in the tube, the anode high voltage P/S should be switched off in a time less than 20 ms at least. Therefore the stored energy in the capacitors could not damage the tube. A crowbar will be used for a short circuit of the anode power supply.
- Screen grid interlock includes bleeder resistors to avoid the auto-polarization, and spark gap to protect against overvoltage.
- Control grid interlock also includes bleeder resistors and spark gap to protect against reverse current.
- RF interlock: RF driver power must be switched off in less than 2 us when arcs at the tube as well as circulator and RFQ.

OTHERS FOR RF AMPLIFIER

Circulator and Load

The circulator is used to protect the tube from over-reflected RF power from RFQ. The circulator is being manufactured by AFT in Germany. The return loss will be higher than 26 dB and insertion loss will be less than 0.2 dB with a temperature control unit (TCU). The circulator load or dummy load will be used a water load of 125 kW made by Altronic Research Inc or Bird. High power measurements by calorimeter method with precise temperature and flow meters are possible at a load.

Transmission Lines

6-1/8" 50 ohms coaxial lines are designed to deliver the RF power to RFQ up to 100 kW (CW). Any additional cooling is not needed for the transmission lines because maximum RF power capacity is 150 kW at 165 MHz. But be careful the heavy humidity inside lines and connection between inner connectors during installation.

Directional Coupler

Directional coupler is for monitoring and controlling the RF powers which are forward and reflected power. Directivity is less than -20 dB for correct power measurements. Two dual directional couplers will be used to at output stage of amplifier and input stage of RFQ.

FUTURE WORKS

Present design study on the 100 kW RF amplifier are explained with each parts. Key part is FPA of TH781 which is purchased to the Thales including factory acceptance test for high power test. The amplifier systems with power supplies, an IPA and an LLRF control are fabricating in domestic companies. The manufacturing of a 100 kW tetrode RF amplifier is not so easy with poor experiences. Therefore, understanding the RF system, control system, vacuum tube as well as RFQ, and collaboration are essential with manufacturers, designers, operators by supervisor of KBSI. The RF amplifier will be fabricated and tested with a dummy load by the end of 2015 and can be commissioned with RFQ later. A high power RF amplifier with TH781 was fabricated and tested up to 230 kW at 175 MHz for IFMIF project [7]. Exchange of information and experience with the institute and related laboratories will be very useful mutually for present projects or future works.

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