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DEVELOPMENT STATUS AND CONSTRUCTIONAL FEATURES IN RF HPA FOR ALS-U PROJECT AT LBNL

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Abstract

The Advanced Light Source Upgrade (ALS-U) project at Lawrence Berkeley National Laboratory (LBNL) is major upgrade of the ALS that involves the design and installation of a new Accumulator Ring and an upgraded Storage Ring. The RF High Power Amplifier (HPA) with 60 kW CW output power at 500 MHz is a complex and very costly piece of equipment that will provide high power RF to the accelerating cavities in Accumulator Ring. This paper presents the main technical specifications / requirements, features, development status and construction details of various subsystems of the HPA which is being built under contract by R&K Company and with engineers at LBNL providing technical oversight and inputs. The HPA detailed design and construction drawings / documents were completed by the vendor and the Final Design Review was successful. Presently, manufacturing of the HPA is in progress. The HPA is self-protecting and the main features consist of a distributed control system employing extensive monitoring of various signals; slow and fast interlock responses; finite state machine controls; and built-in fault tolerance to RF or DC power supply module failures. The theoretical high reliability (MTBF ~ 135000 hours) and high availability (~99.997 %) requirements of the HPA requires redundancy in RF modules and DC PS modules for delivering a minimum 48 kW RF output under module fault conditions.

INTRODUCTION

The ALS-U project at LBNL is aimed to create a world class facility to provide users with bright, high-coherent-flux soft x-rays that are unmatched in the world now. The ALS-U project will provide an increase in brightness and coherent flux of soft x-rays (at1 keV) of at least two orders of magnitude beyond today's ALS capabilities. It will also provide infrared and hard x-ray capabilities comparable to the present-day ALS. There will be an upgraded Storage Ring (SR) optimized for low emittance, high soft x-ray brightness & coherent flux and a new Accumulator Ring (AR) for full-energy swap-out injection and recovery of beam bunch trains. The new AR RF system is comprised of two independent AR RF accelerating cavity subsystems, each having a low-level RF controller, an RF HPA, high power circulator, high power RF switch, rigid coaxial transmission lines, and ancillary support equipment. Each will provide the requisite controlled, stable high power RF to the two normal conducting RF cavities so as to generate the required 500 kV cavity voltage to deliver energy to the circulating electron beam in AR.

The solid-state based RF HPA (see Fig. 1) is a complex piece of equipment that is the preferred topology in most Laboratories for new projects and for replacing earlier obsolete tube based RF amplifiers because of known benefits like graceful degradation, no high voltages, high efficiency, modularity, high MTBF, and low phase noise.

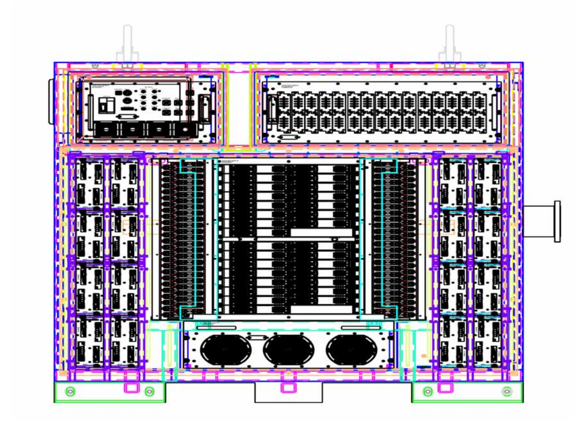

Figure 1: Front CAD view of the HPA cabinet.

HPA MAIN SPECIFICATIONS

The HPA main specifications are tabulated in Table 1.

Table 1: HPA Main Specifications

Specification	Value
Center Frequency	500.394 MHz
1dB BW	≥ 5 MHz
1dB Output Power	≥ 60 kW CW
Input Power	≤ 0 dBm
Wall plug Efficiency	≥ 55 %
Group Delay	≤ 200 ns
Spurious	≤ -80 dBc
Stability (long term)	≤ ± 0.5 dB ; ≤ 10°

HPA TOPOLOGY & REDUNDANCY

The HPA is built using modular topology with redundancy by utilizing 96 Final Amplifier (FA) RF modules and 30 DC Power Supply (PS) modules for the power transistor drain bias circuits. There is also DC PS redundancy for transistor gate bias circuits and also for the control system. The HPA has high redundancy requirement such that with failures up to 10 % of Amplifier Modules and/or failures of up to 15 % of DC PS modules, it shall still deliver at least 48 kW RF output power as required for beam operations.

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AC POWER DISTRIBUTION

The HPA utilizes 3-phase, 480 VAC input for the DC PS modules and 1-phase, 120 VAC power the control system. The 3-phase AC power is distributed to the 30 DC PS modules using six, 3-phase solid-state relays that are switched on in staggered manner to limit the inrush current. For fault isolation and protection, fuses are incorporated in various branch circuits. All 3-phase and 1-phase AC line voltages and line currents are monitored & interlocked.

DC PS MODULES

The DC power for the RF modules is derived from 30 DC PS modules (GP100 from GE), arranged into two groups of 15 DC PS modules, that are operated in parallel with load sharing between the two separate DC group bus bars 1 & 2. The bus bars are sized for handling high currents of up to 1.2 kA. The high current bus bars are fully enclosed. Each DC PS module has an efficiency of about 95 % and each module delivers about 5 kW DC power in such parallel operation. The DC PS modules are compact in size and they are air cooled as they have high efficiency. The DC PS modules have a reliability of approximately 190,000 hours. Each of the two DC group bus bars powers 48 RF final amplifier (FA) modules. The DC voltage for transistor drain bias is programmable from 30 to 50 VDC with a nominal drain operating voltage of 45 VDC. The DC PS modules have a low ripple voltage of less than 100 mV for frequencies up to 20 MHz, so the RF output signal spectrum will have lower spurious levels. For personnel safety from stored energy, the discharging resistors are incorporated that will discharge the output capacitors of the DC PS modules and FA modules to less than 1 V in about 20 s.

RF AMPLIFIER MODULES

The required high power RF is produced by amplification of a low-level RF input signal through a cascaded chain of Preamplifiers (PA), Driver Amplifier (DA) having redundancy, followed by a divider and 96 parallel-connected FA modules having redundancy, whose output powers are combined using a RF combiner. The overall gain of the amplifier chain is about 80 dB. The RF FA modules (see Fig. 2) are based upon latest 9th generation LDMOS FET part number BLF978P from Ampleon. The FETs are operated in class AB mode in push-pull configuration. The FA modules also incorporate circulators with reject loads at both the input side and output sides of the FET, so as to protect the FET from reverse power. The input and the output baluns in the matching circuitry were realized using semi-rigid coaxial cables of characteristic impedance of 25 ohms and with sufficient power handling capability. The output circulators from Valvo are rated to 1kW and the reject loads are rated 1.6 kW, providing sufficient margin to handle any reverse power from the combiner. The measured RF output power at the FET is about 750 W with nominal drain voltage of 45 V, and has a drain efficiency of 70 %. Two sub-FPGA controllers inside the FA unit monitors and controls the various signals for two FA modules on each side.

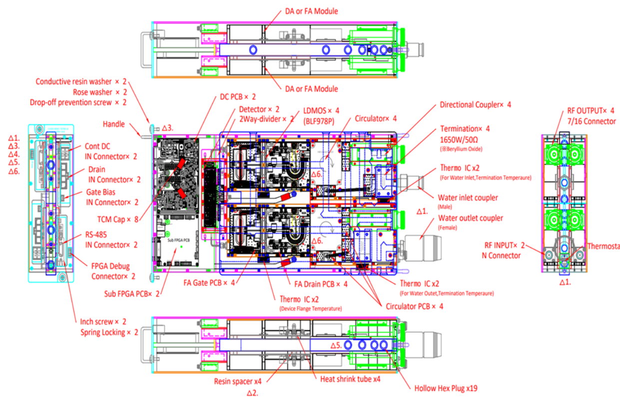

Figure 2: The RF FA module.

THERMAL MANAGEMENT

Proper thermal management is important since the drain efficiency of the FETs is about 70 % in class AB mode. Water cooling is used to remove the major heat from DA, FA and combiner, while a heat exchanger is utilized to remove the residual heat power from other ancillary components, so as to keep cabinet air temperature below 45 °C. Two FA units (8 FA modules) are series-connected in each of 12 parallel water branch lines having a flow rate of 7.5 l/m between the inlet and outlet manifolds. The intended water inlet temperature to the first FA unit is about 23 °C, but the second FA unit, being series connected, operates at an elevated water temperature. Cooling channels were made in the copper-based cooling plate that houses two RF FA modules on either side of the plate. Thermal simulations of FA cooling plate were performed at its full RF output power (~ 750 W) for cases of no reflection as well as the worst case condition of full RF reflection. The thermal simulation results of the temperature profile under worst operating condition at the second FA unit at full reflection show conservative results with higher temperature profiles, however, the measured results show about 10 - 15 °C lower temperature profiles likely due to convective and radiative heat transfer.

RF DIVIDER AND COMBINER

The RF output signal from the Driver Amplifier is split by a 1:48 RF divider followed by 1:2 divider so as to generate 96 RF drive signals for the 96 FA modules. The 1:48 divider has a similar coaxial construction as the 96:1 combiner. The outputs from the 96 FA modules are connected using very low loss cables to a 96:1 RF combiner. The combiner is made of copper and utilizes water cooling. It is rated for 100 kW CW power and it has combining efficiency of about 95 %. The FA modules are interchangeable among any of the input ports of the combiner and the output power should not vary by more than 100 W for such interchanges. Sufficient high power handling and rugged 7/16 DIN coaxial connectors are used at the RF input ports and 6 1/8” EIA rigid coaxial line is used at the RF output port. A high power circulator rated to 100 kW CW will be installed at the HPA RF output to direct any reverse power from the RF accelerating cavity to an 80 kW reject load.

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WATER COOLING

The water cooling removes majority of heat power from the HPA and ensures operating temperature of heat generating components remain well below their maximum specifications, also improving the reliability of the HPA. The HPA water cooling is designed for specified maximum inlet flowrate of 95 l/m at 23 °C with a nominal supply pressure of 8.3 bar and return pressure of 1.4 bar. There are a total of 13 parallel water branch lines between the water inlet and outlet manifolds, one branch line catering to one series-connected PA, DA, and RF combiner with a nominal flowrate of 4 l/m and the remaining 12 branch lines catering to series-connected 2 FA units (8 FA modules) per branch line with a nominal flow rate of 7.5 lpm. The water-cooling channels in the cooling plate that houses 4 FA modules, are laid out to pass underneath the transistor, output matching, circulator, and reject load that are the major sources of heat. The water temperature rise at the HPA outlet is estimated to be about 8 °C at full 60 kW RF output. The water piping layout is carefully designed and guarded to minimize the potential for splash or leakage of water onto nearby electrical components. A water leak interlock is also implemented. Quick disconnect connectors are utilized for easy connections without needing hand tools.

HPA CONTROLS

The HPA contains extensive monitoring, as well as control, display, warnings, interlocks, data logging of large number of various signals parameters in HPA. The HPA is a fully self-protecting system. The HPA can be operated in local mode from front panel HMI or in remote mode from an EPICS IOC using the Ethernet IP interface. In ALS-U, the HPA will also be interfaced to Equipment Protection System through optical fiber cables for the RF permit signal inputs and internal HPA fault outputs. The HPA will have two categories of fast (< 10 us) and slow (few 10 s of ms) interlock response speeds. The HPA control system will be comprised of a distributed network of controllers viz., one PLC, one main FPGA controller, and 55 sub-FPGA controllers located in various modules and subassemblies within the HPA. The HPA control system utilises fast sampling 16-bit ADCs and 12-bit DACs for high accuracy. The main FPGA controller communicates with the DC PS modules using the I^2C interface for controlling and monitoring its parameters. The PLC communicates with main FPGA using a Modbus TCP interface and the main FPGA communicates with the 55 sub-FPGA's using a multi-drop Modbus RTU interface. The threshold set points for warning and interlocks for various signal parameters can be set in the HMI through a password protected authorized access. The HPA will also implement a Finite State Machine for sequenced control of the start-up, operation, transition to fault states, and the shut-down processes of the HPA. The HPA control system will be fault tolerant to the failures of the FA RF modules, DC PS modules etc., and continue HPA operation seamlessly without interruption. The various warnings, first fault, interlocks and fault messages are logged with respective time stamps for aiding with troubleshooting and for making any investigations later, so as to get to root cause of such problems or issues.

HPA RELIABILITY PREDICTION

The theoretical reliability prediction of the HPA was done by estimating the Mean Time Between Failures (MTBF) of each subsystem of the HPA by considering the components that typically exhibit high failure rates. The components with much smaller relative failure rates have been ignored. The manufacturer provided MTBF data was utilized for the DC PS modules. The reliability probabilities having an exponential distribution parameterized on failure rate were determined considering a scheduled maintenance frequency every two weeks. For the modules with built-in redundancy, such as FA modules and the DC PS modules, the reliability probability was determined from binomial distribution probabilities with required number of operational modules out of the total number of the FA modules and the DC PS modules as required for generating at least 48 kW RF output power. The overall reliability of the HPA is obtained as multiplication of the reliability of the subsystems. Following such process, the overall reliability (MTBF) of the HPA was estimated to be ~ 135,000 hours. For estimating the availability of HPA, the Mean-Time-To-Repair (MTTR) was reasonably assumed as 4 hours, and so the HPA availability was estimated to be ~ 99.997 %.

CONCLUSION & TESTING PLANS

The detailed design, construction drawings, and documents have been completed by the vendor as per the LBNL specifications & requirements, with technical oversight and input from engineers at LBNL. A desk review of the design for conformance to relevant US standards was carried out by Underwriters Laboratory (UL), a Nationally Recognised Testing Laboratory (NRTL) and the discrepancies were satisfactorily closed by design rework / modifications as needed. The Final Design Review for the HPA was successful and the comments and recommendations were satisfactorily closed to enable the vendor to proceed to start manufacturing the HPA. The manufacturing of the HPA is in progress, with majority of construction work of HPA cabinet and various subsystems in advanced stages of completion. The HPA is scheduled for preliminary field inspection & evaluation by UL (NRTL) at the factory site, followed by comprehensive Factory Acceptance Tests (FAT). Upon successful completion of the FAT, the HPA will be shipped to LBNL and the final field evaluation by UL (NRTL) at LBNL and the Site Acceptance Tests (SAT) will be completed before the two HPA's are finally installed with the two AR RF accelerating cavities.