ISBN: 978-3-95450-219-6 ISSN: 2226-0366 doi: 10.18429/JACoW-LINAC2024-TUPB089

ANALYSIS OF REDUNDANCY DESIGN AND RELIABILITY ESTIMATION OF 60 kW CW RF HPA FOR ALS-U PROJECT AT LBNL

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Abstract

The two units of 60 kW CW AR RF High Power Amplifier (HPA) are critical major equipment in new RF system for ALS-U project at LBNL and so it has been designed and built with a modular redundant topology having large array of 96 RF final PA modules (each delivering ~ 700 W RF output) that are combined in parallel, and large 30 DC PS modules (each ~ 5 kW DC power) operating in parallel for achieving very high reliability (MTBF ~ 135,000 hours) and availability (~ 99.997%) of RF HPA which is essential for continuous 24/7 beam operation. The redundancy design to modules failures is such that in the event up to 10% failures of RF PA modules and/or up to 15% failures of DC PS modules the HPA still can generate minimum 48 kW CW RF output that is needed for full beam power and so RF power headroom of 12 kW is built in. The operating power levels and temperatures of all components in HPA are well below to their maximum ratings for high reliability. The MBTF values of subsystems in HPA has been estimated based on components with high failures rates. The reliability probabilities having exponential distribution parameterized on failure rate were determined and the binomial distribution used for modules having redundancy. This paper presents such redundancy design analysis of HPA to such modules failures to achieve such minimum output power. Also, the Availability (~99.997%) and the Reliability (MTBF ~ 135,000 hours) Estimation analysis of the overall HPA with such redundancy to modules failures is presented.

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 and 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 AR RF HPA will provide the requisite controlled, stable high-power RF to each 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 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.

The design and construction features of various subsystems in the AR RF HPA viz., AC, DC, PA modules, combiner, LCW cooling, controls, etc. has been described in Ref. [1]. The HPA has been designed and manufactured thorough a joint effort of engineers from LBNL and engineers at vendor R&K Company Ltd., Japan and a picture of the HPA taken during the factory acceptances test is shown in Fig. 1.

Figure 1: Photo of the AR RF HPA taken during FAT.

HPA MAIN SPECIFICATIONS

The HPA main specifications are tabulated in Table l.

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°

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HPA REDUNDANCY ANALYSIS

To have high redundancy and graceful degradation of output power, the HPA has been built using modular topology by utilizing 96 Final Amplifier (FA) RF modules (each delivering ~ 700 W) that are combined using RF output combiner and 30 DC Power Supply (PS) modules (each ~ 5 kW DC power operating at ~ 45 VDC) that are operating in parallel for providing the drain bias to RF PA modules LDMOS FET (BLF978P from Ampleon). There is redundancy also built into the driver amplifier stage.

However, the HPA does not have complete redundancy with regard to all of its components, meaning that there are few single points of failures in the HPA RF amplification chain such as the input RF switch, preamplifier (operating at low power), the input splitter and the output RF combiner, which is passive component having negligible failure probability. The HPA has high redundancy specification such that in the event up to 10% failures of RF PA modules and/or up to 15% failures of DC PS modules, the HPA can still generate at least 48 kW RF output power that is needed for full beam power taking into account the transmission line losses from the HPA to RF cavity.

Further taking into account the loss in module output circulator, directional coupler, cables and connectors of total about 0.2 dB and the loss in output combiner of about 0.2 dB, we obtain the RF output power with no failed RF PA modules to be about 61.3 kW.

In the event of 10% of 96 = 10 failed RF PA modules we obtain the RF Output Power of about $700*(0.955*86)^2/96 = 49.2$ kW, which meets the minimum 48 kW output power specification. Although one would think intuitively from conservation of energy that a 10% failed RFPA modules should result in only 10% reduction and not about 20% reduction of the RF Output Power but actually in the event of failed RF PA modules due to the imbalanced condition in combiner will result in fraction of RF power from the operating modules that gets reflected by the combiner and most of fractional reflected powers will get to the reject load of the circulators at the output of the failed RF PA modules and they do not contribute to the RF Output Power. So, the conservation of energy remains satisfied when account for all such powers in the HPA system. Therefore, the reduction in the RF Output Power is about 20% in the event of 10% failed RF PA modules.

In the event of 15% of 30/5 DC PS modules having failed, the HPA still has adequate DC power required for 60 kW output power with no RF PA module failures. Conservatively assuming that RF PA module has efficiency of 60% (actually better ~ 70%) the DC power needed for each RF PA module is about 1166 W. For 96 RF PA modules the DC power needed is 1166 W * 96 = 111.93 kW and the DC power from remaining 25 DC PS modules is 5 kW * 25 = 125 kW. So, it meets the 60-kW output power.

Also, in the event of 10% failed RFPA modules and 15% failed DC PS modules, the DC power needed is 1166 W * 86 = 100.27 kW only, which can be met by remaining 25 DC PS modules. Thus, the HPA can generate the specified min 48 kW output with 10% failures of RFPA modules and 15% failures of DC PS modules.

Table 2 summarizes the power redundancy analysis described above.

Table 2: HPA Power Redundancy Analysis Summary

Percentage Failures DC PS Modules	Percentage Failures RF PA Modules	RF Output Power (kW)
0	0	≥ 60
0	≤10 %	≥ 48
≤ 15 %	0	≥ 60
≤15 %	≤10 %	≥ 48

Furthermore, in the event of greater than 10% failed RF PA modules and greater than 15% failed DC PS modules, the HPA has been designed and manufactured to continue to operate seamlessly and deliver the RF output power that is achievable from the remaining modules and thereby continue to have graceful degradation in RF output power.

HPA RELIABILITY AND AVAILABILITY ESTIMATION

For achieving high Reliability of the HPA for continuous 24/7 operations, the HPA has been designed and built with strong considerations to reliability and the operating point of various electrical components having regard to voltage, current, power dissipation and temperature are well below their respective maximum values. LCW water cooling subsystem is used in HPA to remove the dissipated power in the RF PA modules and also an air to water heat exchanger is utilised to remove residual heat so as to keep the HPA internal air temperature below 45°C when operating at full 60 kW output power. The main critical component in the RF PA module is the LDMOS FET and its junction temp at full 60 kW output power has been indirectly determined from measured data to be less than 120°C which is much below its datasheet specified maximum of 225°C, thereby providing high reliability and increased life of the RF PA modules. Further by incorporating redundancy in the major power generating RF PA modules and the DC PS modules, the overall HPA reliability is further increased.

The theoretical reliability prediction of the HPA was done by estimating the Mean Time Between Failures (MTBF) of each major subsystem of the HPA by considering the components that typically exhibit high failure rates which are obtained from the relevant tables provided in the

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reliability standard MIL-HDBK-217F which in fact provides conservative data estimate values. The components with typically 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 and so the mission time was taken to be two weeks, equal to 336 hours.

For the modules with built-in redundancy design, such as RF PA modules and the DC PS modules, the reliability probability was determined by summing of the 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. A small MATLAB code was written and used for aiding with such lengthy calculation and summation in binomial distribution over-running the number of operating modules (index) from 86 to 96 for RFPA modules and from 25 to 30 for the DC PS modules. Such calculation result in MATLAB turned out to be very close to 1 (actually 0.99999….) limited by resolution of number representation in MATLAB. The overall HPA reliability is obtained as product of the reliability of the subsystems.

Following the aforesaid process, the reliability estimation analysis is shown in Table 3. So, 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 and conservatively taken to be as 4 hours. So, the HPA Availability = MTBF/(MTBF + MTTR) was estimated to ~ 99.997%. Although another definition of Availability uses the Mean Down Time (MDT) instead of the MTTR, where the MDT is the MTTR plus any other contributors to the down time such as time spent in not able to diagnose and detect the root cause of the failure. However, there are extensive monitoring, display and interlocks with time stamps incorporated in the HPA control system using PLC and FPGA controllers which greatly aids in the diagnosis and troubleshooting of the HPA, so the MDT can be reasonably taken to be as the MTTR. The time needed for replacement of any failed RF PA modules or PS module is much lesser of about 30-45 minutes only. So, the actual Mean Time to Repair is expected to be much less than 4 hours and so the estimated availability of the HPA would be improved which is even better.

Table 3: HPA Reliability Estimation Analysis

Sl no	**HPA Subsystem**	**MTBF (hours)**	**Reliability Probability P = exp(-T/ MTBF) (T = 336 hours)**
1	AC distribution	461,826	0.9992
2	Control	300,979	0.9989
3	Pre-amp modules	1,153,464	0.9997
4	Driver amplifier modules	1,335,805	0.9997
5	Final amplifier modules	4,870,080	0.9999 (each) (MATLAB code for k = 86:96 sum(binopdf (k,96,0.9999)) ~ 1.0000
6	Power supply modules	190,000	0.9982 (each) (MATLAB code for i = 25:30; sum(binopdf (i,30,0.9982)) ~ 1.0000
7	LCW	10,041,150	~ 1.0000
8	Combiner	22,002,200	~ 1.0000
	Overall reliability probability		**0.99752**
	Overall HPA MTBF		**135,315 hours**

ACKNOWLEDGEMENTS

The authors sincerely acknowledge the help and support of many other people who have directly or indirectly made contributions in this AR RF HPA project.

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