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THE ANALYSIS OF MODULES FAILURE IN SOLID-STATE AMPLIFIER FOR HIGH CURRENT RFQ

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Abstract

The new RF system of Radio Frequency Quadrupole accelerator (RFQ) in ADS project at IMP was upgraded in the beginning of 2017, the original tetrode amplifier was replaced by two new solid-state amplifiers (SSA) for proton acceleration, they are the same 80kW rated power to combine at least 120kW inside the cavity through two uniform couplers. But for SSA, since too many power modules were set on the amplitude and phase for power combination, one or some damaged circulator (including sink loads) may lead to high risk of whole RF system fail. Especially, according to experiments and simulation, when the transmission line between two different level combiners meets a specific condition, the scattering parameter of system would have a great fluctuation, even cut-off, if some problems happen in circulators or sink loads. In this paper, the simulated methods aiming at simulating the multi-level synthetic amplifying were introduced in detail, the failure analysis and related experiments focusing on amplifying links of SSA under the special circumstances was also presented simultaneously.

INTRODUCTION

Since the old 200kW tetrode amplifier was operated in high current beam without a circulator, two new SSAs was considered to replace it on site due to their specialties of stable, sustainable and reliable, whose cavity operates in 162.5MHz, the dissipated power reaches up to approximate 90kW, and especially, the beam power has also 21kW while 10mA beam current was applied [1]. thus, some special technologies of new generation SSA were developed for this kind of high intensity accelerator in BBEF, such as two types of reflection power experiments on module including long-term continuous wave power and four times pulsed power. Due to too high power, the design of power module and combiner need to be considered the scattering parameters in the situation of mismatch resulting from the multi-port balance [2].

Figure 1: The four-vane RFQ cavity with two couplers.

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SSA MODULES FAILURE

In our case, over 120 power modules are integrated through several level synthesizers for full power output, which shows in Fig. 1, and every module can provide maximum 850W RF power for 80kW power output even when one pre-amplifier fails. Last June, 19 power modules were burned at the same time, within them, almost all power transistors, circulators and sink loads (connected directly with the circulators) were damaged on the same time only to be replaced. When failure happened, the power values was recorded from many directional couplers in the screen of control system, the specific values were presented in Fig. 2.

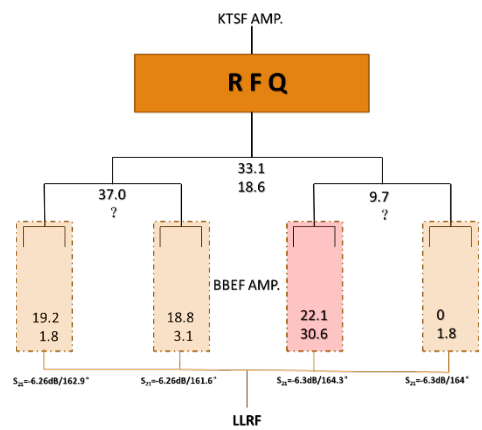

Figure 2: The screenshot of failure situation.

From it, our SSA was consisted of four 20kW sections to integrate gradually for providing 50 or 60kW RF power (without beam or 10mA beam) for separate coupler simultaneously. And after basic analysis and check on the machine, one most possible reason for accident should be too sensitive of driving signal interlock in 3# section comparing other three sections, the input signal of 3# section was shut down suddenly because of abnormal interlock during the operation, other three sections were influenced to increase rapidly power at that time due to LLRF close loop on the amplitude modulation. Furthermore, the weird location of all injured modules indicate that some inappropriate RF configuration need to be removed and optimized.

In this dangerous situation, more than half transistors, circulators and sink loads in 3# section were burnt severely. However, it is very difficult to explain clearly the phenomenon which the broken modules are all belong to 3# section, especially on the left side.

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ANALYSIS FROM SIMULATION

For the convenience of analysis, a simple model of multi-port power combiner was created in simulation software Microwave Studio to figure out the variation regularities of the scattering parameter. According to the simulated results, if any one port was open or short, the parameter S_{21} along transmission line on this port have a very great fluctuation along 360^0 phase, even when the wavelength equal to a certain value, the scattering parameter take dramatic turn to block the RF signal, the sweep results in CST while the wavelength was changed gradually, which indicates there be some reflected power points to block the power through combiners when λ meet certain demand.

Generally, the most advantage of SSA is stable output while one or some modules fails, except for the decreasing of output power. For instance, n modules fail in a 7kW combiner with 9 modules, the output power was degraded $(9-n)^2/9^2*100\%$. However, the situation would be much complicated while the circulators inside the module fail rather than field-effect transistors, the same as some phase shift and short circuit resulted in high reflected power, n ports network was gained through the matrix analysis [3], Sm=SII+SIIIΓ(1-SIIII)-1SIII [4] is degraded matrix of n ports network with the arbitrary load, m ports in them with no loads (full reflection), and according to symmetry and lossless of nine ports combiner, the scattering matrix of 8-1 power synthesizer is:

$$S=\begin{bmatrix} -\frac{7}{8} & \frac{1}{8} & \cdots & \frac{1}{8} & \sqrt{\frac{1}{8}} \\ \frac{1}{8} & \ddots & \cdots & \frac{1}{8} & \vdots \\ \vdots & \vdots & \ddots & \frac{1}{8} & \vdots \\ \frac{1}{8} & \frac{1}{8} & \frac{1}{8} & -\frac{7}{8} & \sqrt{\frac{1}{8}} \\ \sqrt{\frac{1}{8}} & \cdots & \cdots & \sqrt{\frac{1}{8}} & 0 \end{bmatrix}_{(9*9)}$$

the degraded matrix was gain easily,

$$S=\begin{bmatrix} \frac{1}{64e^{2\alpha}+56}-\frac{7}{8} & \frac{1}{64e^{2\alpha}+56}+\frac{7}{8} & \cdots & \frac{1}{64e^{2\alpha}+56}+\frac{7}{8} & \frac{\sqrt{2}}{32e^{2\alpha}+28}+\frac{\sqrt{2}}{4} \\ \frac{1}{64e^{2\alpha}+56}+\frac{7}{8} & \ddots & \cdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{1}{64e^{2\alpha}+56}+\frac{7}{8} & \cdots & \cdots & \ddots & \frac{\sqrt{2}}{32e^{2\alpha}+28}+\frac{\sqrt{2}}{4} \\ \frac{\sqrt{2}}{32e^{2\alpha}+28}+\frac{\sqrt{2}}{4} & \cdots & \cdots & \frac{\sqrt{2}}{32e^{2\alpha}+28}+\frac{\sqrt{2}}{4} & \frac{1}{8e^{2\alpha}+7} \end{bmatrix}_{(8*8)}$$

When one output port in them was short, the degenerate matrix [5] can be deduced as above. So, when the phase of short port was 0 or π, the minimum S_{11} of 0.0667 and reflected power of input port would be gained simultaneously. and when phase was 900, S_{11} get the maximum value of -1 to mean the full power reflection [6]. The S_{11} and Sn1 were plotted according to the formula in Fig. 3.

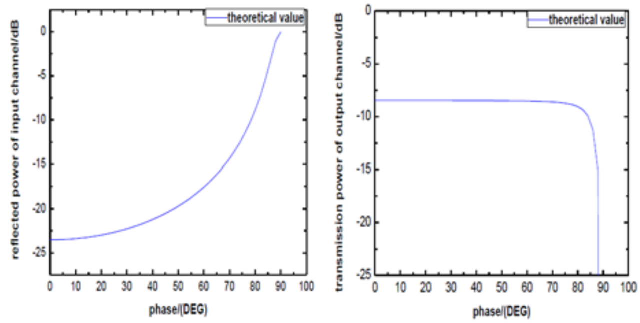

Figure 3: The simulation of wavelength influence.

EXPERIMENTS FOR SIMULATION

Obviously, the results from formula had a good agreement with the CST simulated ones. then a targeted experiment was prepared for this situation, which takes advantage of a three-level combiner/ divider to measure the scattering parameter while any one port mismatches (short or open circuit). A 1-8 combiner/ divider was re-fabricated into three-level components for changing the wavelength between the different levels in Fig. 4.

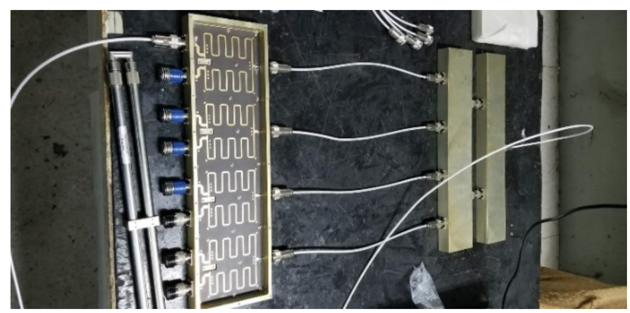

Figure 4: A special test stand with three-staged combiner.

For these three-level combiners [7], the failure of one port would lead to change greatly, even block completely RF signal. And according to the rule of scattering parameter, S_{11} along the transmission line of full reflection point will fluctuate severely, which shows in Fig. 5.

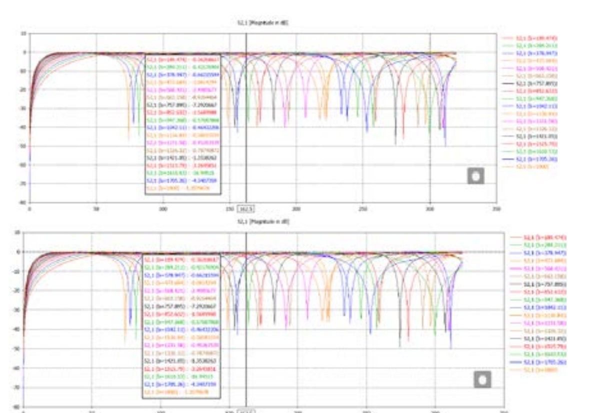

Figure 5: The S_{11} plot along the different transmission line while one port short or open circuit.

The measured results indicate the simulation of one port failure be right in this three-stage combiner testbench

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shown in Fig. 6, the VNA can gain precisely scattering parameters and phase when certain one port was connected with the phase shifter and open/short components.

The measured S_{11} were displayed in Fig. 6 when all ports matched except one port mismatched, the S_{11} close to -20dB indicates a very good matching from left figure. And in the right figure, the Max. S_{11} would reach up to -5dB which means serious mismatching when one port fails. As a result, the scattering parameter was analysed to find out the specific regularities while the length of the phase shifter was changed gradually.

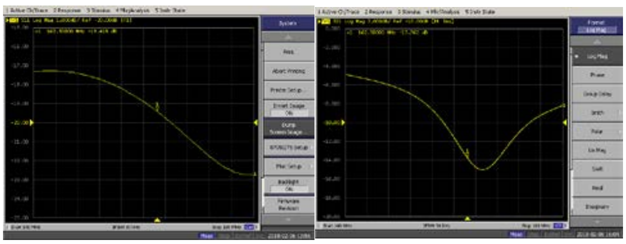

Figure 6: The S_{11} results when all match and one port fail.

According to the measurements, the electrical length of one phase shifter was about 118^0 on 162.5MHz. Three phase shifters can measure the S parameter of whole range while the one port failure, the worst matching (that is the block point) was shown in Fig. 7.

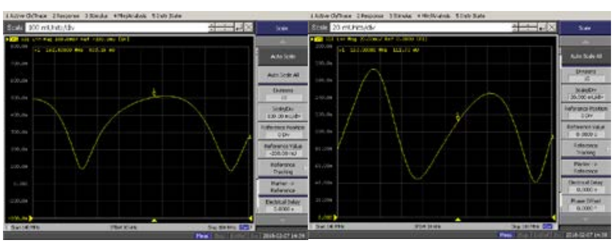

Figure 7: The worst S_{11} and S_{21} results along the full length while one port fails.

CONCLUSION

From the simulations and related experiments as above, it is impossible that the power modules with circulator were damaged or burned down due to the severe power reflection, one reason was unreasonable electrical length between the different two level of combiners when uncertain one or several ports mismatch, while the phase meets the particular demand, the power transmission may be attenuated extremely between the modules, even block power completely. The simulation focused on it and measurements on related experiments agree well each other. New SSA design should consider phase relationship while one port fails according to its operating frequency, which can improve greatly reliability and reduce the risk of failure and its cost.

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