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RF SYSTEM OPERATION OF HIGH CURRENT RFQ IN ADS PROJECT

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Abstract

New RF system has been upgraded several times for high-current operation, especially for extra beam power and detuning angle. The current was increased gradually resulting in more and more frequency detuning, and an effective method is to tune the temperature of cavity to compromise detuning. The power dissipated in cavity and high intensity beam are approximately 120kW resulting in too many power modules operated in the high risk of failure. The specific analysis and simulation were introduced in detail.

INTRODUCTION

Since 2014 RFQ system accelerated successfully 10mA proton beam in Chinese Accelerator Driven System (ADS) project [1], RF system has updated few times for stable and secure operation. Original power source was a tetrodes type without circulator, which is potential risk while the high current beam coming from frequency detuning. The newest RF system was two 80kW solid-state amplifiers with many small circulators inserted in power modules for feeding power to separate coupler (shown in Fig.1), and frequency stability was carried out through adjusting temperature of inlet water, whose operating scheme need to be analysed beam load carefully.

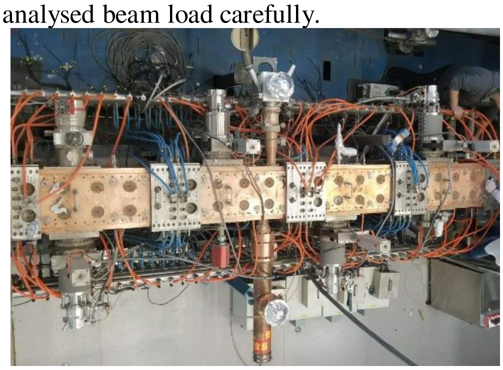

Figure.1: ADS RFQ cavity with its two couplers.

Furthermore, the multi-layer of power synthesis in amplifier may happen severe failure or module damage causing great economic loss and delay of project process.

BEAM LOADING

According to the theoretical calculation, the optimum detuning is just for the case of the single cell cavity [2].

$$tan\Psi = -\frac{I_{b,e}R}{(1+\beta)V_c}sin\emptyset$$

However, for ADS RFQ, the synchronous phase was varying vastly along the whole electrode, its range is from -23^0 to -90^0, whose distribution is shown in Fig.2.

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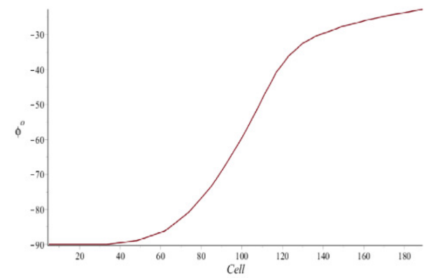

Figure.2: the synchronous phase in RFQ along 186 cells.

Generally speaking, the eigen-frequency of the RFQ was solely determined by its geometry and size, not the beam. But while the high current beam was accelerated, the reflected power increases greatly, which indicates the frequency of the RFQ change by the beam.

In fact, for linear accelerators, the negative synchronous phase results in a capacitive impedance model.

$$R_b = \frac{I_b}{V_c}cos\emptyset$$

$$C_b = -\frac{I_b}{V_c\omega}sin\emptyset$$

The frequency shift from beam-inducing detuning can be calculated by the following expression:

$$\Delta f = -\frac{fI_b}{4V_c}\left(\frac{r}{Q}\right)sin\emptyset$$

Therefore,

$$tan\Psi = -\frac{I_{b,e}R}{(1+\beta)V_c}sin\emptyset = -\frac{P_b}{(1+\beta)P_c}tan\emptyset$$

which is the expression for optimum detuning, if the impedance angle is replaced by the synchronous phase. And effective synchronous phase of the RFQ,

$$\overline{\emptyset} = -\cos^{-1}\left(\frac{\sum_n A_{10,n}\cos\emptyset_n}{\sum_n A_{10,n}}\right)$$

with the parameters of the RFQ, we'll obtain $\overline{\emptyset} \approx -33^0$.

The beam-inducing detuning evaluated with $\overline{\emptyset}$ is:

$$\Delta f = -\frac{P_b}{(1+\beta)P_c}tan\emptyset \approx -0.95kHz$$

which is much smaller than the experiment value, which indicates the effect from quadrupole mode should not be neglected when calculating the impedance angle.

Thus, the new calculation was modified according to measurement situation, and the effective RF phase was estimated as the following way:

$$\overline{\emptyset}_h = -\tan^{-1}\left(\frac{\left|\sum_n A_{10,n}\sin\emptyset_n\right| + \frac{N}{2\sum_n L_n}\sum_n A_{0,n}m_nL_n}{\sum_n A_{10,n}\cos\emptyset_n}\right)$$

With the parameter of the RFQ with the quadrupole part, then we'll obtain $\overline{\emptyset}_h = -78.5^0$

The beam-inducing detuning evaluated with $\overline{\emptyset}_h$ is,

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$$\Delta f' \approx -7.8kHz$$

So the beam-inducing field phase variation：

$$\Delta\emptyset \approx 4.2^0$$

The frequency detuning and phase shift after considering quadrupole mode agree well with the commissioning experience and operation.

TWO-PORT CONFIGURATION [3]

According to RFQ beam dynamics design, nearly 31.5 kW beam power and 97 kW dissipation power of the RFQ cavity will be transmitted by couplers. If the two couplers are set incorrectly, the total power of over 120kW may concentrate on one coupler and may exceed the capacity of single coupler. Therefore, the proper configuration of the two couplers lead to a critical technical issue for the stable running of the whole RF system.

According to the RF theory, the loaded Q_L of a cavity with two couplers is:

$$\frac{1}{Q_L} = \frac{1}{Q_O} + \frac{1}{Q_{ext,1}} + \frac{1}{Q_{ext,2}}$$

$$Q_O = (1+\beta)Q_L$$

then

$$\beta = \frac{2Q_O}{Q_{ext,1,2}}$$

where Q_O and Q_{ext} are unloaded and external quality factor, respectively. The coupling constant β of the cavity without beam must meet the requirement $\beta = 1 + Pi/Pc$ so that the couplers are in critical coupling condition when beam is accelerated, where Pi and Pc are the beam power and cavity power respectively. According to the definition of coupling constant, for each coupler

$$\beta_{1,2} = \frac{Q_O}{Q_{ext,1,2}} = \frac{\beta}{2}$$

therefore, for the acceleration of 15 mA proton beam β=1.32, and for each coupler $\beta_{1,2} = 0.66$.

When setting up the two couplers a vector network analyser (VNA) is utilized to measure the S_{11} scattering matrix which is related with coupling constant [3], and the two couplers ports are measured separately at the same time. The measured coupling constant $\beta^*_{1,2}$ has a relationship with the real $\beta_{1,2}$ as follows

$$\beta^*_{1,2} = \frac{\beta_{1,2}}{1+\beta_{2,1}}$$

Furthermore, the coupler port must be open when the other coupler is measured.

Finally, we set the S_{11} scattering matrix of each coupler as -7.3 dB [4] to correspond the coupling constant β of 0.66, which is adjusted to display on the VNA on site and shown in Fig.3, this configuration has never been modified during the subsequent conditioning and beam commissioning. According to the S_{11} scattering matrix the line impedance of each port is 33 ohms. The RF system with two coupler ports has been simulated with Microwave Studio to prove that the two-port configuration is correct.

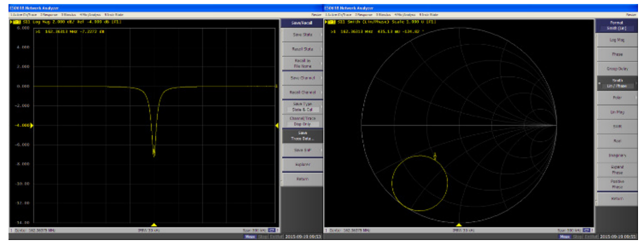

Figure 3: the measured coupling factor on site.

FAILURE OF POWER MODULE

Two new solid-state amplifiers are the same 80kW rated power, whose separate manufacturer (Beijing BBEF science & technology co., ltd. and Chengdu Kaiteng sifang digital radio & TV equipment co., ltd.) implies the output power with different power gain and phase. The attenuator and electric phase shifter were adjusted carefully for the balance when the total power reaches to the goal. The LLRF interface was shown in Fig.4, which can integrate the functions of tuning, monitoring and interlocking in it.

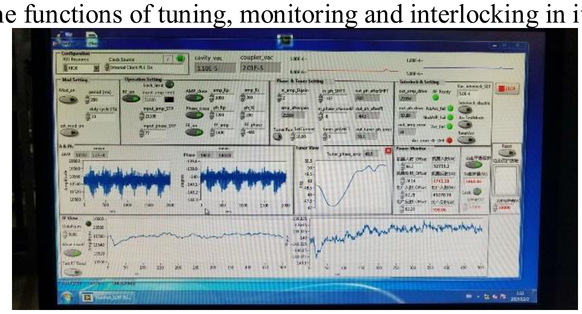

Figure 4: the LLRF interface with multi-function.

Since the long-term operation of high power, some minor injuries in modules accumulated may lead to very serious accident. Last June, 19 power modules were burned at the same time, within them, almost all power transistors and sink loads (connected with the circulator) were damaged to be repaired for a long time. When failure happened, the display of all power values was recorded in control system, the specific values were as follows.

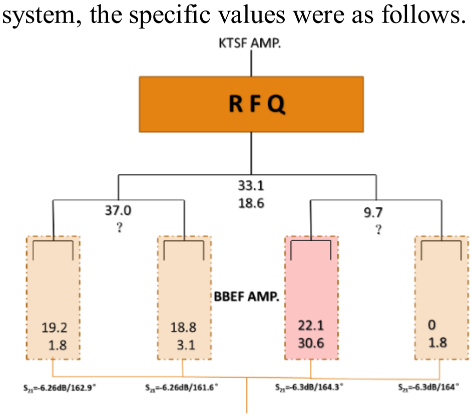

Figure 5: the layout of new RF system and failure record.

Two sets of SSAs both are consisted of four 20kW sections to integrate gradually for providing 50-60kW RF power for separate coupler simultaneously, and due to the

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different output characteristics, LLRF has to adjust the offsets of output gain and phase in the beginning.

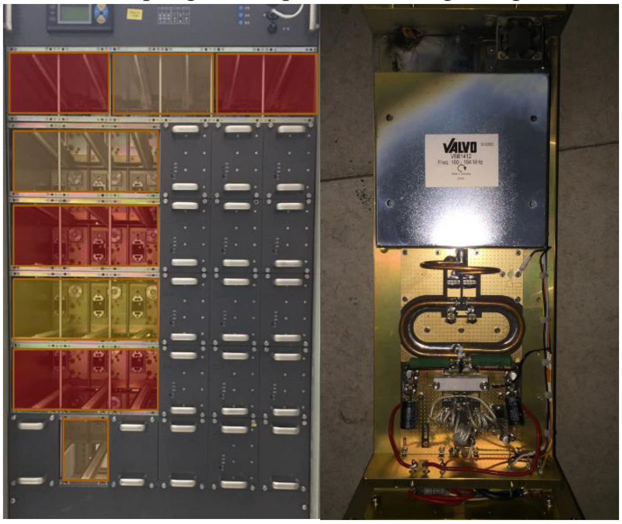

Figure 6: the damaged modules in 3# section.

One important reason for accident is too sensitive of driving signal interlock in 3# section. Since the output power of 3# section was shut down during operation, other three sections were influenced in the same time due to the connection from combines of whole system. Thus, all transistors and sink loads were burnt severely not to repair, which is represented in Fig.6.

And according to the analysis of simulated model, while the wavelength between two-layer combines was a particular value, the scattering parameter take dramatic turn to block the RF signal, Fig.7 shows 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 equals to certain values.

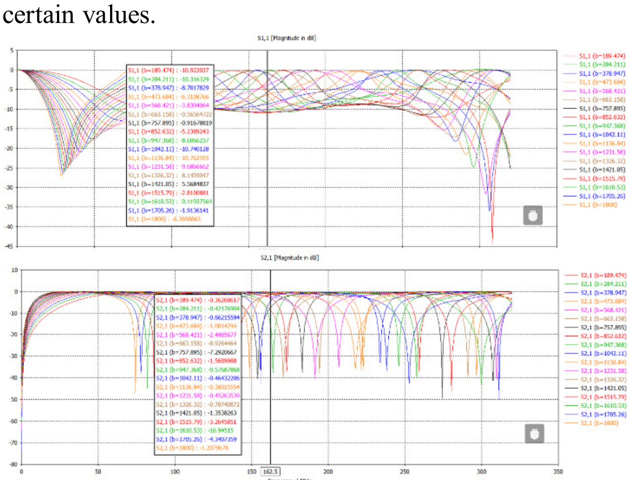

Figure 7: simulation focused on the wavelength influence.

When wavelength was an inappropriate value on site, two factors lead to this accident, one is too high driving power due to the close loop operation of LLRF, the other is shutting down of 3# section resulted from its own amplitude interlock of input power (too sensitive to operate stably). Now, the logic of interlock and LLRF are both modified according to the analysis as above, and the abnormal increase of reflected power has never observed again. The new function of power balance was added to prevent from the big difference between two amplifiers output during operation.

COMMISSIONNING

Considering the previous operating experiences [5], it takes two weeks on the new process of conditioning of RF system, it started on April 2016, and the coupling coefficient Until now, the 10mA pulsed beam has been accelerated several times and all the parameters well meet the commissioning requirements of the RFQ.

For whole ADS, the 25MeV 10mA proton beam was accelerated successfully through downstream four superconducting sections, and CW beam of 25MeV was observed at the subsequent experiment in the case of limit of neutron dose, the current was controlled carefully in below 200nA.

SUMMARY

As a high current proton accelerator, RFQ system in ADS was designed and optimized carefully according to it's the beam loading calculation. As we all know, for RFQ it is very hard to estimate the synchronous phase due to the huge change along the electrode structure, a new method to obtain it and the calculated results were reasonable comparing the RFQ operation on site.

The preliminary RF design including two new SSAs has been accomplished and verified, and the main parameters of RF system were analysed and calculated by the electromagnetic software CST microwave studio. The main features in the RF system was the two-port configuration which indicates a new method to solve too high-power fed into the cavity, and subsequent successful conditioning of a new heavy-ion RFQ with the same configuration proves the design and manufacture of the RF system are all correct and can well meet the requirements of the RFQ accelerator.

Finally, the high power SSAs have the potential risk since their complicated RF structure. the reason of module was focused on wavelength within combiners according to the analysis, some specific experiments are in process for improving and optimizing this problem.

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