THE STUDY OF ELECTROMAGNET COMPENSATED HIGH POWER FERRITE CIRCULATOR OPERATION WITH SUPERCONDUCTING RF CAVITY

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Abstract

In a high power RF system for accelerator application, the circulator is very important for protecting klystron or IOT from damage due to high reflection power from the cavity. When there is no beam current passing through the superconducting RF cavity of the accelerator, almost 100% RF power will be reflected from the cavity even the cavity is on resonance. The circulator shall be able to forward the reflected power to the load and remain good matching and isolation condition between ports at klystron and the cavity. However, for a ferrite material based circulator, the magnetic field within circulator would be temperature dependent which would cause the variation of input return loss and isolation between ports. Additional DC current driving electromagnet field is thus required for compensating the temperature variation. Even with the compensating DC current, the circulator is still not ideal for practical operation especially when the performance of the circulator is strongly phase dependent. The phenomenon observed in actual operation with one set of SRF systems in NSRRC is thus reported in this article.

INTRODUCTION

For the Taiwan Photon Source (TPS) 3GeV synchrotron light source in NSRRC, two sets of KEKB superconducting cavity with 300kW RF power sources are in routine operation since summer of 2014. The 300kW RF power is delivered by a klystron (by Thales) which is powered by a PSM type klystron supply unit (High voltage power supply by Ampegon). The RF power is thus transmitted from klystron through WR1800 waveguide via a three ports 350kW circulator (made by AFT) to the SRF cavity. The reflection power from SRF cavity would be directed to 350kW ferrite load (by AFT) by the circulator to avoid high reflected power back to the klystron. Such high power RF stand is quite popular and widely adopted by industry and scientific applications. Among the subcomponents of such high power RF system, the klystron or IOT is the most critical and important part which needs comprehensive protection to prevent it from damage such as overheating, too much RF reflection power and RF arc. The proper operated circulator can avoid the klystron from high reflection power and window arc. However, the adopted circulator is not simply a passive component without external control; on the contrary, the ferrite material based circulator need additional electromagnetic field to compensate the magnetic field variation due to temperature changing. Therefore, the circulator with a well setting temperature compensating unit (TCU) is thus required for reliable protection of the klystron.

In the routine maintenance of SRF cavity in NSRRC, the coupler aging with various loading angle of the cavity are applied weekly for clean up the condensed gas over the coupler to reduce the trip rate caused by multipacting during high power and high beam current operation. Since the reflection power at circulator port#1 is highly sensitive to the phase of the reflection power at circulator port#2, the reliable operation of the circulator during coupling aging period with varying cavity loading angle become a challenge. With the non-proper setting of the TCU, the high power RF system would be trip by high reflection power at klystron during coupler aging. The vacuum condition procedure would be interrupted and taken longer time due to such annoying situation. The basic property of the ferrite based high power circulator would be described first and the strategy to eliminate such interrupt with its side effects is discussed later.

THE CIRCULATOR AND ITS TCU

The setup of high power RF stand in NSRRC is shown in Fig. 1. A waveguide bridge is setup between circulator and the cavity for phase tuning. The circulator property is controlled via coil current (I_{coil}) output by the TCU while the temperature of inlet/outlet water (T_{in}&T_{out}) and ambient temperature (T_{amb}) determine the I_{coil}. The difference of Tin and Tout can obtain ΔT which can represent the heat loss or the temperature increasing within the ferrite material. Before high power test on circulator, the circulators have excellent performance in low power test by Vector Network Analyzer (VNA). TCU is even not necessary during low power test. However, when RF power is applied through the circulator, proper setting of the weighting factors between temperatures and I_{coil} become important to remain low input VSWR at port#1.

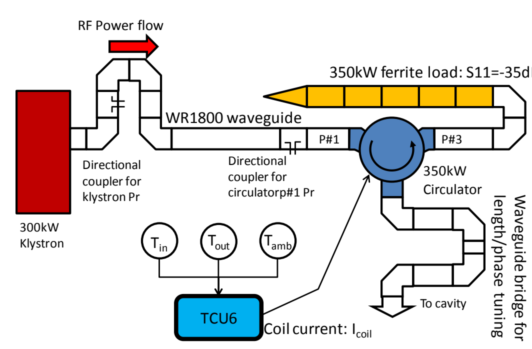

Figure 1: The RF power stand for SRF cavity in NSRRC.

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The Commission of High Power Circulators

The circulator shall operate under CW at various power levels without introducing significant change of reflection power at klystron port. Since the load at circulator port#2 is SRF cavity and the length between the circulator and the SRF cavity is not well known yet when the circulator was just arrived NSRRC, the commission of the circulator is applied under 4 lengths of shorted waveguide at port#2 and remain input return loss higher than 26 dB under various power level and in long term condition. In the beginning, there is only one factor of ΔT to adjust the response of I_{coil}. There is no way to optimize the port#1 VSWR of circulator to be lower than 1.1 at various shorted phase at circulator port#2 as shown in Figure 2. Later, upon our request, AFT release the in-depth control software to fine adjust the operation parameters to be able to have satisfactory input return loss under various power level and various shorted length/phase@port#2 as shown in Fig. 3.

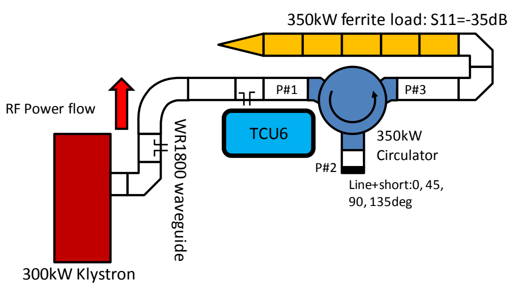

Figure 2: the test stand for circulator commission.

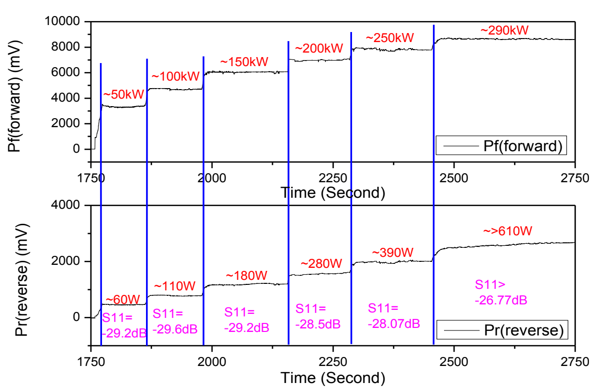

Figure 3: The forward and the reflection power of the klystron with one blanked length at port#2 of circulator.

Coupler Aging Under Various Loading Angle

The KEKB SRF cavities use coaxial input coupler to feed RF power to the cavity. A portion of the input coupler is immersed inside the liquid helium vessel and is in cold temperature below 273K. The gas would be easily condensed on the surface of the input coupler. The condensed gas would cause vacuum burst when high RF power is fed and causing multipacting [1]. To reduce trip rate caused by vacuum burst of the condensed gas during daily operation, weekly RF condition of the coupler vacuum is thus necessary. The coupler vacuum condition is applied by varying the loading angle of the cavity. The signal frequency is unchanged while the resonant frequency is tuned by the cavity tuner according the required loading angle which is obtained by adjusting the phase shifter within tuner loop. The loading angle will change from +45° to -45° which represents 90 degree phase change of the reflection power to the circulator as shown in Fig. 4. Besides changing loading angle, the coupler of SRF module still needs to be applied RF condition as the cavity is on-resonance at 2400kV and detuned, corresponding to 180 degree phase changing of the reflected power to circulator. The circulator shall be able remain port#1 VSWR below 1.1 under 225° phase changing of reflected power and various power level.

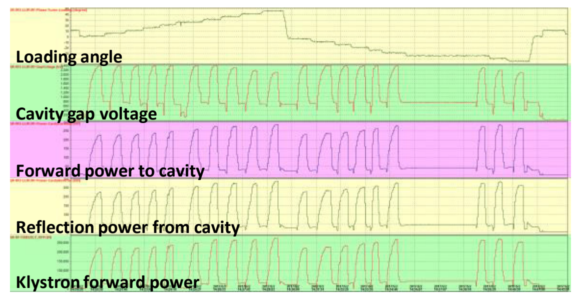

Figure 4: The coupler vacuum condition by varying cavity loading angle.

ON-SITE TUNING OF TCU

When the circulators were just started commissioned in 2013 with room temperature PETRA cavity and 300kW klystron, the reflection power at cavity side is not so high and tuning the settings of TCU is not necessary. After the 1st phase machine commission for vacuum cleaning of vacuum chamber of storage ring in TPS, the SRF cavities were installed in 2014. The RF vacuum cleaning of cavity couplers become a weekly regular maintenance activity. Under such wide phase changing of the reflected RF power, the settings of TCU need simultaneous tuning with the changing of loading angle and the forward power of klystron to prevent over high reflected RF power to the klystron. However, at certain loading angle, due to fast changing of the temperature of circulator, the changing of I_{coil} was also fast and large which would lead to too high reflected power shortly. Besides, the temperature of the coupler also increased quite fast at certain loading angle as high RF power was applying. To avoid such phenomenon, the way to diagnose the property of the circulator with the SRF cavity is described below:

The Choice of Coil Current: On-Site VSWR

Since the impedance of SRF cavity changes a lot between on and off-resonance, the reflection power at klystron side also changes a lot under the same setting of TCU. Such situation would make the choice of proper operation coil current to be difficult. To find the optimum coil current at any status of SRF cavity, the on-site low power VSWR measurement setup by vector network analyzer (VNA) is applied as shown in Fig. 5. The relative high return loss at klystron side under the preferred coil current of circulator can be clearly observed. This can help to visually see the return loss at klystron side without regarding the phase of cavity while varying coil current. The result of the return loss at circulator port#1 of klystron side is shown in Fig. 6. The return loss shall be close between the on- and off-resonance frequencies.

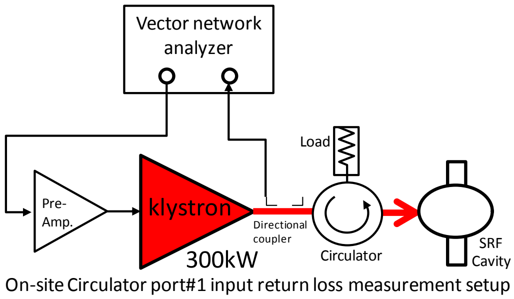

Figure 5: On-site high power measurement of return loss of klystron side.

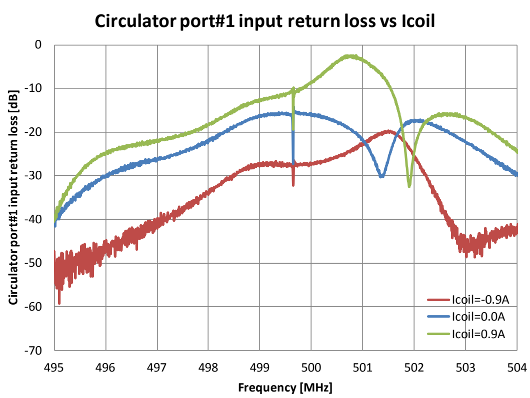

Figure 6: The on-site low power return loss measurement result versus coil current of TCU.

The Changing of External Q of SRF Cavity

The tuning of coil current can obviously optimize the reflection power at klystron side by the above method. However, the side effect of the coil current tuning is also observed during coupler RF vacuum condition: the changing of external Q (approximately equal to loaded Q) of the SRF cavity. The modification of external Q of cavity can change the required RF power for building the same gap voltage within the cavity. Such phenomenon may induce invisible high electric field of standing wave within the coupler even at the ceramic window. To avoid this, the Qext of SRF cavity is also measured by the setup as shown in Fig. 7.

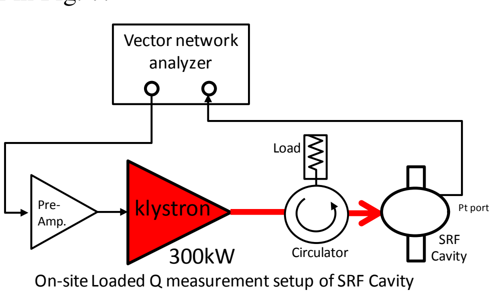

Figure 7: On-site loaded Q measurement of SRF cavity.

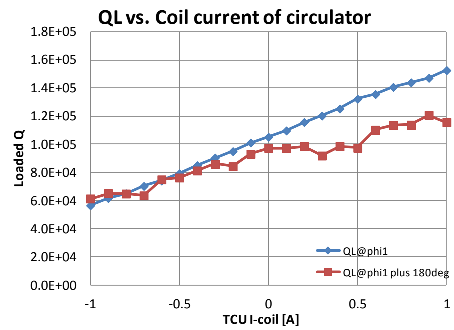

Figure 8: eliminate the changing of external Q of SRF cavity versus coil current by adding 180° phase shift transmission line at cavity side.

The variation of external Q of SRF cavity caused by coil current can be slightly cured by adding or removing a section of transmission between circulator and the cavity which as shown in Fig. 8. Such way can reduce the excited electric field of the standing wave within the coaxial coupler of SRF cavity as well as the temperature increasing rate during coupler aging.

CONCLUSION

A high power circulator is a very important component within a high RF power stand for RF power source protection. In this article, the basic commission method of a three ports ferrite material based circulator is described. The stable operation at fixed four phases of reflection power can be reached by in-depth tuning of the operation parameters. As the phase of reflected RF power changing during coupler aging of SRF cavity, the control of coil current become difficult. An on-site measurement of return loss at klystron side is applied for fine tune the coil current of circulator. Besides the reflected power, the circulator also changed the impedance of the SRF cavity as coil current changing. To reduce the variation of external Q of the SRF cavity, a length of transmission line is added between circulator and the SRF cavity. By the above two ways, the high power circulator can operate stably for protecting klystron during any loading angle of SRF cavity and avoid potential damage risk to the input coupler of KEKB SRF cavity.

REFERENCES

[1] Chaoen Wang *et al.*, "Strategy towards non-interrupted operation of superconducting radio frequency modules at NSRRC," presented at IPAC'17, Copenhagen, Denmark, May 2017, paper MOPVA098, this conference.

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