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Analysis of superconducting cavity quench events at SSRF

HOU Hong-Tao(侯洪涛)[1,2,3] LIU Jian-Fei(刘建飞)[1,3;1)] ZHAO Yu-Bin(赵玉彬)[1,3]
ZHAO Shen-Jie(赵申杰)[1,3] ZHANG Zhi-Gang(张志刚)[1,2,3] LUO Chen(罗琛)[1,3]
FENG Zi-Qiang(封自强)[1,3] MAO Dong-Qing(毛冬青)[1,3] ZHENG Xiang(郑湘)[1,3] LI Zheng(李正)[1,3]

[1] Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China
[2] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3] Shanghai Key Laboratory of Cryogenics & Superconducting RF Technology, Shanghai 201800, China

Abstract: Quench is important and dangerous to superconducting RF cavities. This paper illustrates the mechanism of quench and how a quench detector works, and analyzes the quench events happening during beam operations and cavity conditioning. We find that the quench protection is mostly triggered by some reasons such as fluctuation of cavity voltage, multipacting or arc, rather than a real cavity thermal breakdown. The results will be beneficial to optimize the operation parameters of superconducting cavities, to discover the real reasons for beam trip by quench interlock, and to improve the operation stability of superconducting RF systems.

Key words: superconducting cavity, quench, beam trip

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1 Introduction

Superconducting cavities are adopted in the storage ring at Shanghai Synchrotron Radiation Facility (SSRF) to provide energy for electrons. The cavities and RF window are protected by fast interlock signals from quench, coupler vacuum, arc, helium vessel pressure and ready-chain, which includes other vacuum signals and cooling water temperature, water flow-rate, and so on. The cavity will be damaged during a thermal breakdown, called quench, when there is no proper and fast protection. Thus, the superconducting cavities are usually protected by a quench detector, which will shut off the power of RF source in tens of microseconds when quench happens. Quench can happen during the test, processing and operation with a beam. Different kinds of reasons to bring on the quench interlock are analyzed and discussed in this article. This study will be beneficial for the operation of superconducting cavities at SSRF.

2 Superconducting cavity quench

The theory of quench can be found in many research articles and books. The main reason for quench is that there are defect or impurity areas on the inner surface of a superconducting cavity. The surface resistance will increase exponentially with temperature and result in local overheating, which makes the cavity partially normal conducting [1, 2]. This case is often associated with strongly enhanced power dissipation. The unloaded quality factor will decrease and the coupling strength will decrease too. The cavity voltage and the reflected power will become smaller. The vacuum in the cavity will become worse. For the increased power dissipation, there will be more consumption of liquid helium and more output of helium gas. The helium vessel pressure and the venturi differential pressure, which indicates the helium gas flow rate, will increase sharply due to the increased power dissipation. The temperature of cavity surface, where sensors are placed, may be found to rise, too.

Cavity quench is detected by the quench detector mounted in the SRF control rack. It can work in processing mode without a beam and in run mode with a beam. Eq. (1) shows how the quench detector works.

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1) E-mail: liujianfei@sinap.ac.cn

The quench detector will send out a quench interlock signal whenever Condition 2 is satisfied in processing mode or both Condition 1 and 2 are satisfied in run mode.

$$\begin{aligned} &V_{\rm probe} < k_{\rm p} \times V_{\rm set} && \text{Condition 1,} \\ &V_{\rm forw} \times k_{\rm r} - V_{\rm refl} \times k_{\rm B} > k_{\rm Z} && \text{Condition 2,} \end{aligned} \quad (1)$$

where,

$V_{\rm probe}$: Detected voltage from the transmitted power,

$V_{\rm forw}$: Detected voltage from the forward power,

$V_{\rm refl}$: Detected voltage from the reflected power,

$k_{\rm p}$: Set point of transmitted power,

$k_{\rm r}$: Set point of reflected power,

$V_{\rm set}$: Set voltage of transmitted power,

$k_{\rm B}$: Tuning parameter "Balance" of quench detector,

$k_{\rm Z}$: Tuning parameter "Zeromask" of quench detector.

The quench detector compares the detected voltage with the forward power, the reflected power, the transmitted power from cavities, and the set voltage value. When the cavity is operated without beam current, the quench detector can be set to work in processing mode. If there is a thermal breakdown, or if anything else makes the reflected power smaller than the forward power, Condition 2 will be fulfilled and the quench detector will send out an interlock signal to shut off the RF power. When the cavity is operated with beam current, the quench detector has to be set to the run mode. The reflected power is smaller than the forward power whenever there is a beam in the storage ring because the cavity not only needs power to construct the cavity voltage to accelerate electrons, but also needs power to be transferred to beam. Condition 2 is thus satisfied and this is the reason why the quench detector should work in run mode when the cavity is operated with beam. Whether the quench detector will send out the interlock signal depends on the transmitted power. Therefore, whenever Condition 1 is fulfilled, the quench detector working in run mode will send out the interlock signal without distinguishing if there is a real thermal breakdown or anything else that can make the transmitted power smaller.

3 Analysis of quench trips

Quench is dangerous to superconducting RF cavities, so there must be quench protection. Real cavity thermal breakdown used to happen during cavity conditioning without a quench detector. The burst disc on the safety valve was broken because of high pressure in the helium vessel increased by the extra exhausted liquid helium. The quench protection during beam operation ever happens because of multipacting or fluctuation of cavity voltage. When this kind of quench protection happens, there is no increase of helium vessel pressure or venturi differential pressure. It is found that the cavity voltage has some kind of fluctuation or a decrease huge enough to fulfil Condition 1 in Eq. (1).

3.1 Quench protection by real thermal breakdown

The real cavity quench was observed, shown as Fig. 1, when the superconducting cavity at position 1 in the storage ring of SSRF was processed. The quench detector sent out an interlock signal to shut off the RF power. The temperature sensor on the top of the cavity changes about 17 K from 8.6 K to 25.7 K. The helium vessel pressure increased about 15 mbar, which is higher than the normal value 1200 mbar, and the venturi pressure increased about 15 mbar sharply.

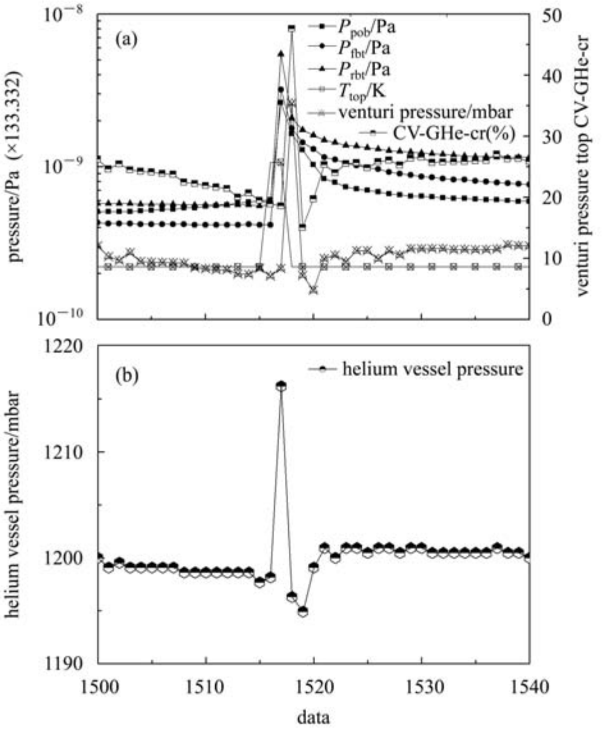

Fig. 1. Cryogenics parameter variation when a real quench occurrence. $T_{\rm top}$ is the temperature of cavity top, venturi pressure is the differential pressure of venturi, CV-GHe-cr is the control valve of cold helium gas return. $P_{\rm pob}$, $P_{\rm fbt}$ and $P_{\rm rbt}$ are the vacuum pressure at RF window and both ends of the beam tubes. Helium vessel pressure is the pressure in helium tank with 1200 mbar normal operation value controlled by PID loops. The horizontal axis is data points related to recording time.

The CV-GHe-cr, which is the control valve for helium gas cold return, was controlled by proportional-integral-derivative (PID) loop to open sharply to more than 45% in order to let the extra helium gas out of the helium vessel to decrease the pressure and to protect the cavity. And when this quench happened, it could be seen that the cavity vacuum became worse from the cold cathode gauge installed near the RF window and at both ends of the beam tubes.

3.2 Quench protection by fluctuation of cavity voltage

It is believed that most quench interlocks are not caused by real cavity thermal breakdown because there is no detected sharp increase in helium vessel pressure at the same time. The superconducting cavities are controlled by the digital Low Level Radio Frequency (LLRF) system when operated with beam current [3]. If there is a cavity voltage fluctuation caused by the instability from LLRF system or the beam current, the transmitted power will fluctuate following the cavity voltage. The quench interlock will happen when the fluctuation is large enough to make the transmitted power fulfil Condition 1. There is indeed a quench signal captured by the beam trip diagnostic system [4], shown in Fig. 2, and it can be found that the first trip station is the cavity at position 2 by analyzing the time sequence. We can see the fluctuation of the transmitted power, which stands for the cavity voltage. Once one cavity is tripped, the other two cavities will be tripped by quench interlock too. The reason is that when one cavity is tripped, the beam in the storage ring will try to get more power from the other two cavities to keep moving. The cavity voltages become smaller and the digital LLRF system tries to increase the forward power to keep the cavity voltage constant. However, the decrease of the cavity voltages can't be compensated quickly and the quench interlock happens. The set point of transmitted power kp is set to 95%, which means if the transmitted power change is 5% bigger than the set voltage V_{set}, the quench interlock will be triggered. Judging from the waveform captured as Fig. 2 and there is no detected sharp increase in helium vessel or cavity vacuum becomes worse, we think the trip is caused by the fluctuation of cavity amplitude rather than a real thermal breakdown in the superconducting cavity. The PID control parameters of digital LLRF system responsible for the cavity at position 2 were then changed to decrease the fluctuation. This kind of quench fault is extinguished after the control parameters are adjusted properly.

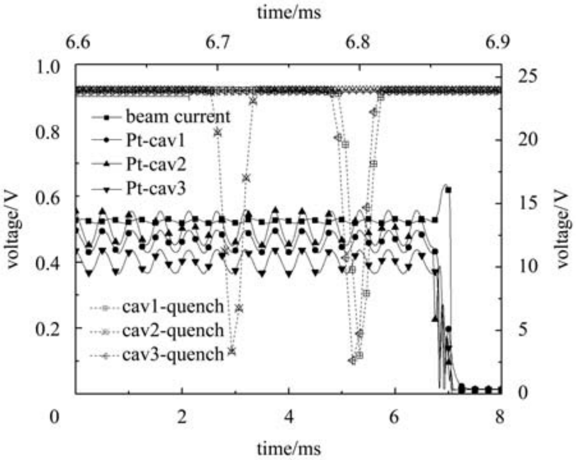

Fig. 2. Quench recorded by the beam trip diagnostic system. Beam current is the detected voltage from a BPM, the Pt of cavities which is a detected voltage from the pick-up power of cavity stands for the cavity voltage amplitude. Quench is the quench interlock signal. Left vertical axis and bottom horizontal axis are for the detected voltages of transmitted power, the right vertical and top horizontal axis are for the quench interlock signals.

3.3 Quench protection by multipacting

Besides the quench caused by thermal breakdown and fluctuation of cavity amplitude, there is another quench coming from multipacting or an arc in the waveguide region or especially around the input coupler. This kind of quench usually happens after about 25 μs, shown in Fig. 3, which is much shorter than that of a real thermal breakdown in the superconducting cavity which happens in several milliseconds. It can be seen that the transmitted power decreased a little first and restored again, then it dropped quickly until quench happened. Thus it is believed that there is multipcating or an arc to drain energy from the cavity. It was found there was no increase of helium vessel pressure or venturi differential pressure. However, there was indeed a sharp increase of cavity vacuum in the beam tube which triggered the interlock of vacuum gate valves at both ends of the cavity. And there was an interlock of maximum reflected power which was the first trip signal instead of cavity quench. It was not conquered by pulse processing with maximum power to 150 kW and maximum cavity voltage to 2.1 MV. And it is found that the frequency with which this kind of quench happened was proportional to the cavity voltage. Therefore the cavity voltage was decreased to 1.4 MV at this moment. It is planned to do a complete thermal cycle of superconducting cavities during the summer shut down time

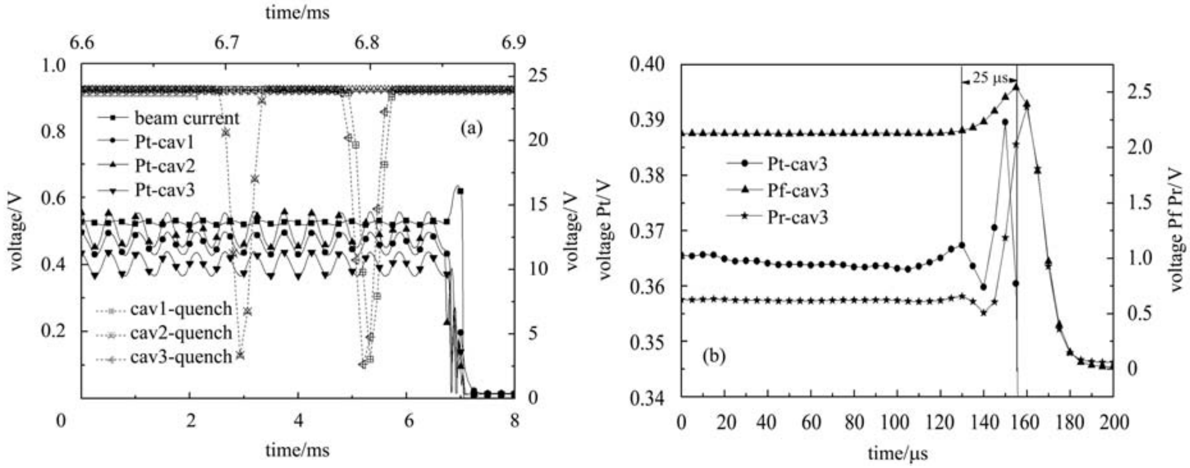

Fig. 3. The quench caused by multipacting or an arc in the region of waveguide coupler. (a) shows that indeed a quench interlock happened and SRF Station 3 was tripped first. (b) shows the transmitted power Pt, the forward power Pf and the reflected power Pr of superconducting cavity 3 when multipacting happened. The time period is only about 25 μs, much shorter than that of a real quench which means the thermal break-down in the superconducting cavity.

of the SSRF machine, which would help to conquer the multipacting and improve the operation performance of this cavity at position 3.

4 Conclusion & discussion

This article analyzes the quench events which happened at SSRF. The results in most of them are not the thermal break-down of a superconducting cavity. The quench which comes from the fluctuation of cavity amplitude has been solved by adjusting the control PID parameter. The quench which comes from multipacting is only solved temporarily, which requires a complete thermal cycle and higher power pulse processing. Due to the gate valves at both ends of the superconducting cavity will be closed when mulipacting happens. As the next step, we plan to optimize the interlock logic of the gate valves in order not to close them frequently.

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