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THE TEST OF RF BREAKDOWNS OF CPHS RFQ

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Abstract

The high accelerating gradient is significant for a compact linear accelerator, and RF breakdowns is a limitation for the high gradient. This work aims to research RF breakdowns of a 325 MHz proton Radio Frequency Quadrupole (RFQ) accelerator of the Compact Pulsed Hadron Source（CPHS）. The breakdown rate (BDR) of the RFQ has been measured. Breakdown waveforms have been recorded, which have been used for counting breakdown time distribution and analyzing the location of RF breakdowns.

INTRODUCTION

Linear accelerator (linac) is an important component of the wide family of accelerators. Since charged particles pass accelerating structures only once in a linac, high accelerating gradient is significant for a compact linac to achieve high energy. The accelerating gradient of a linac is mainly limited by RF breakdown. Up to now, numerous studies have been conducted to research the mechanism of RF breakdown. However, most of them concern about electron linacs whose frequency is usually GHz [1,2]. There has been very little research on RF breakdown of proton linac with much lower frequency. The purpose of this study is to research RF breakdown of a 325 MHz proton Radio Frequency Quadrupole (RFQ) accelerator.

The Compact Pulsed Hadron Source（CPHS）project at Tsinghua University is a university-based proton accelerator platform for multidisciplinary and proton application. The CPHS accelerator consists of an ECR proton source, a low-energy beam transport line (LEBT), a radio frequency quadrupole (RFQ) and a drift tube linac (DTL). The breakdown test was conducted on RFQ of the CPHS project. The main design parameters of the CPHS RFQ are listed in Table 1 [3].

EXPERIMENTAL SETUP

Figure 1 shows the experimental setup. There have three pickups on RFQ cavity so that we can get the RFQ cavity field signal from these pickups. From the directional coupler, we can get the reflected wave. An oscilloscope is used to record these waveforms. Control system help us record some other parameters, like RF power, pulses width, repetition rate, number of breakdowns, and vacuum of RFQ. During the conditioning and beam commissioning of the RFQ, when an RF breakdown happened, the reflected wave amplitude increased and then the breakdown would be detected and the waveforms would be recorded by the oscilloscope.

Table 1: Main Design Parameters of CPHS RFQ

Parameters	Value
Species	Proton
Type	Four-vane
Frequency	325 MHz
Input beam energy	50 keV
Output beam energy	3.0 MeV
Peak beam current	50 mA
Emittance (norm. rms)	0.2 π mm mrad
Maximum surface field	32.1 MV/m
Pulse length	0.5 ms
Pulse repetition rate	50 Hz
RF peak power	537 kW
Beam duty factor	2.5%

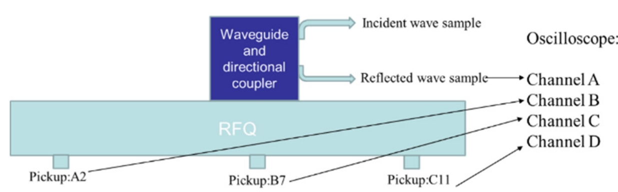

Figure 1: Experimental setup layout.

DATA AND ANALYSIS

Figure 2 is the operation history of CPHS RFQ. The left part and the right of Fig. 2 are corresponding to the conditioning and beam commissioning history of CPHS RFQ respectively. This figure shows the power loss of RFQ and accumulated number of breakdowns with respect to the accumulated number of pulses.

In previous work, CERN has proposed a scaling law to describe the relationship of breakdown rate, accelerating gradient and pulse length for the accelerating structures with very high frequency (usually several GHz) [1]:

$$\frac{E_0^{30}\tau^5}{BDR} = const \tag{1}$$

where E_0 indicates the accelerating gradient (depend on power loss of the structure) and τ the rf pulse length.

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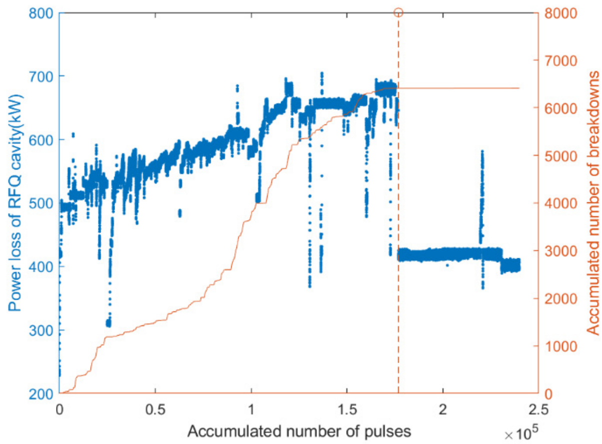

Figure 2: The blue dots represent power loss of RFQ, the red line represents accumulated number of breakdowns.

Based on the scaling law, the “scaling gradient” was defined and has been applied to process conditioning data [2]:

$$E_0^* = \frac{E_0 \tau^{\frac{1}{6}}}{BDR^{\frac{1}{30}}} \quad (2)$$

We want to find the scaling law which is suitable for our RFQ, that is one reason why we conducted this experiment. If we want to find the scaling law, we should measure the BDR of the RFQ under the different pulse length and accelerating gradient after the conditioning finished, since the BDR under a certain pulse length and gradient will decrease during the conditioning. However, we do not finish the whole conditioning at present so that we cannot get the scaling law directly. So, we use the scaling law and the scaling gradient proposed by CERN to process data, Fig. 3 shows the result after applying the scaling gradient to data. After the process, the scaling gradient curve is smoother than before, which indicate that the scaling law proposed by CERN is perhaps suitable for the RFQ with much lower frequency.

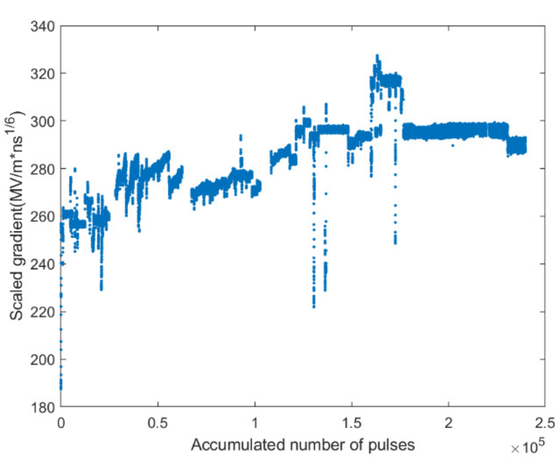

Figure 3: Scaled gradient vs number of accumulated pulses.

BREAKDOWN TIME DISTRIBUTION

The left plot of Fig. 4 is the normal waveforms, the right is the waveforms when a breakdown happened. The blue waveform is the reflected wave, the other three are the pickups’ signal. When a breakdown happened, the reflected wave amplitude increased and would be recorded. Fig. 5 shows the breakdown happened time distribution (pulse length is 50 us). Most of breakdowns happened in the range of 10 us to 14 us, which is closed to the filling time of RFQ. That indicates when the build-up of the field just finished, RF breakdown has a bigger probability to happen.

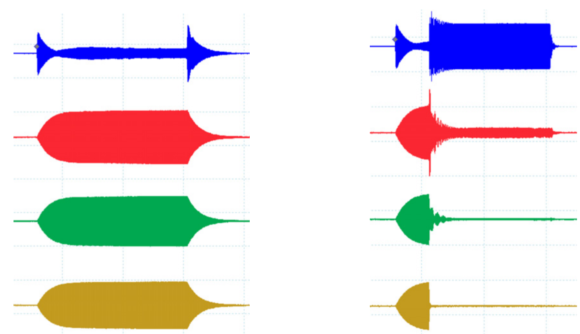

Figure 4: Left: normal waveforms; right: breakdown waveforms.

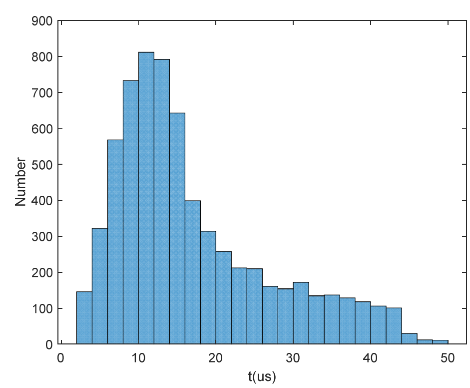

Figure 5: Breakdowns time distribution.

BREAKDOWN LOCATION ANALYSIS

Fig. 6 is an example of breakdown waveforms. Fast Fourier Transform(FFT) has been used to analyze the breakdown waveforms. As shown in Fig. 7, many frequency peaks different from original resonance frequency appeared in breakdown waveforms’ frequency spectrum. 3 mainly component frequencies of breakdown waveforms have been listed in Table 2. The signal of pickup B7, pickup C11, and the reflected wave have the same main component, which indicates that the breakdown probably happened between pickup A2 and pickup B7 as shown in Fig. 8.

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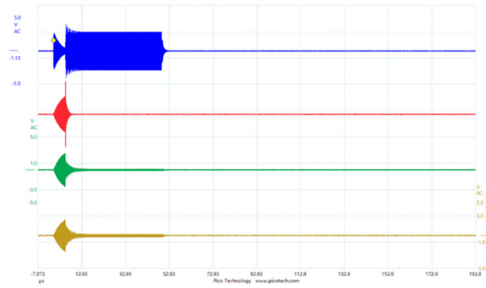

Figure 6: A breakdown waveforms.

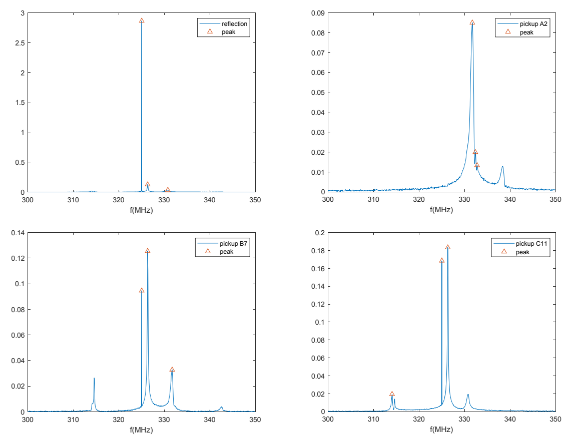

Figure 7: FFT result.

Table 2: Frequency Spectrum

Frequency (MHz)	Peak1	Peak2	Peak3
Reflected wave	325.00	326.31	330.75
Pickup A2	331.69	332.37	332.75
Pickup B7	326.31	325.00	331.69
Pickup C11	326.31	325.00	324.06

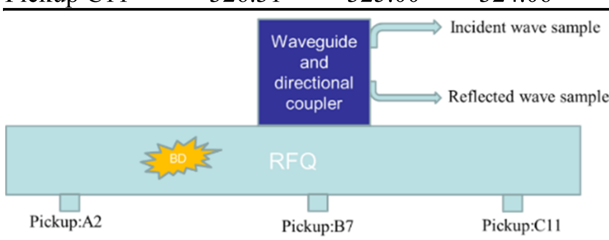

Figure 8: Breakdown location.

In order to explain the frequency spectrum, we have done the CST simulation. Breakdown is accompanied by the formation of a metal ion plasma just above the surface of the breakdown site. When a breakdown occurred, the plasma formed and expanded [4]. The electrodes of RFQ was short-circuited by plasma. The cavity seemed to be divided into two segments, and then each segment has new resonance frequencies. In CST simulation, we use a thin metal cylinder to replace the plasma, as shown in Fig. 9. The simulation results are shown in Fig. 10. Many new modes occur and the field of these modes concentrate on only one side, the cavity seems to be two segments. Pickup on the left side and pickup on the right side will see the different modes, so the frequency spectrum of these two pickups will be different.

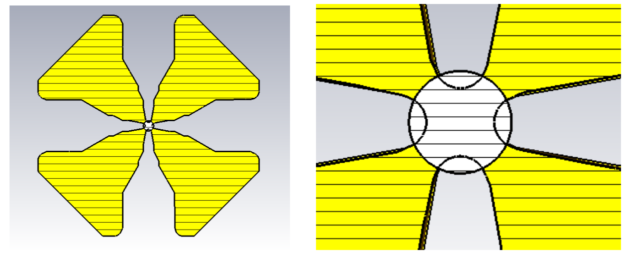

Figure 9: RFQ electrodes model.

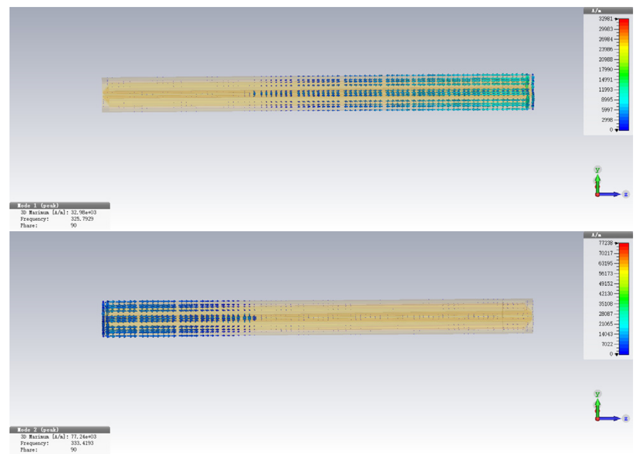

Figure 10: CST simulation results.

CONCLUSION

This work has researched the RF breakdown of CPHS RFQ preliminary. The scaling law proposed by CERN is probably also suitable for RFQ, however it still need more data to validate. RF breakdowns have a great probability to happened when the bulid-up of field just finished .The breakdown location can be determined by analyzing the breakdown waveforms and CST simulation.

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