# PROTECTION OF HARDWARE COMPONENTS WITH HIGH-CURRENT BEAM AGAINST RF TRIPS IN KEKB

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## *Abstract*

In operation with a high-current beam in KEKB, it turned out that an unstable beam resulted from RF trips sometimes causes a large effect on beam-line hardware components. In order to protect the Belle detector and movable masks, "Beam Phase Abort" system was installed. The beam abort kicker is triggered when longitudinal phase of the beam deviates from a nominal range. Another protection was added as a backup: it detects abnormal cavity field and triggers the abort kicker. With these protections the beam is aborted sufficiently fast before the beam becomes unstable. The problems caused by the RF trips have been solved by these protections.

## 1 INTRODUCTION

KEKB is a two-ring, asymmetric-energy electron-positron collider aimed at producing copious B and anti-B mesons as in a factory. In order to achieve high luminosity, design beam current is 2.6 A in Low Energy Ring (LER) and 1.1 A in High Energy Ring (HER). The RF system for the LER consists of eight RF stations: each employs two normal-conducting ARES cavities. The RF system for the HER is a hybrid system composed of five ARES RF stations and eight super-conducting (SC) RF stations [1].

The RF system has been operating very stable. The average number of beam aborts caused by RF trips is about once or twice per day. The number is sufficiently small for heavy requirements on the RF system to operate with the high current beam. It turned out, however, that the trip sometimes causes a large effect on the Belle detector and beam-line hardware components. Although the beam is aborted by interlock signals detected in the RF system, it did not help all cases. Details will be described in Section 2.

To solve the problem, Beam Phase Abort (BPA) system was developed. It generates a request signal to the abort kicker whenever longitudinal phase of the beam is changed due to RF trips. Another protection system was added as a backup to abort the beam when abnormal cavity voltage is detected. They work more reliably and faster than the old abort system. It will be discussed in Sections 3 and 4.

## 2 EFFECTS OF RF TRIPS

### *2.1 Troubles Caused by Trips*

Table 1 shows the number of beam aborts from February to June in 2001. About 30% of the aborts were caused by RF trips. In most cases no serious problems were caused on hardware components. In a few cases, however, the trip caused a large effect as follows, particularly in the HER:

- A large amount of radiation hit the Silicon Vertex Detector of the Belle detector. The worst case was 5 kRad by one trip. Since the performance of the detector can be degraded with an accumulated dose of about 500 kRad, it is a serious problem for long-term operation.
- Sometimes head of movable masks was damaged by unstable beam caused by the trip. Grooves or protrusions were generated on the surface of the mask head, which prevented the beam injection or storage.

Table 1: The number of beam aborts in five months.

| **Period** | **All aborts** | **Caused by RF** |
|---|---|---|
| Feb. 2001 | 86 | 26 |
| Mar. | 98 | 32 |
| Apr. | 104 | 21 |
| May | 84 | 30 |
| Jun. | 98 | 21 |
| **Total** | **470** | **130** |

### *2.2 Phase and Energy Change*

The RF system was designed so that the circulating beam should survive at an accidental trip of one RF station [2]. For example, Fig. 1(a) shows the case when one RF station tripped and the circulating beam of 600 mA survived. When the trip occurs, the longitudinal phase of the beam shifts forward and starts oscillating since the beam energy deviates from the nominal value. The oscillation is damped and the phase is finally stabilised at a different position since the total RF voltage is reduced.

In another case, however, the circulating beam can not survive. As shown in Fig. 1(b), after a station trips, one of the other RF stations also trips due to increased beam-loading resulting from the first trip. Then the phase drastically shifts by more than several ten degrees and the beam is lost. Fig. 2 shows another example, where a crowbar circuit of high voltage power supply for klystrons worked. Since one power supply is operated for two SC stations, an abrupt phase change is resulted and the beam is lost within 400 μs.

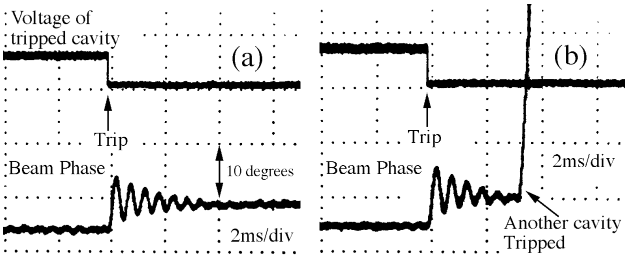

Figure 1: Change of the longitudinal phase of the beam when a RF station trips: (a) the beam survives and (b) the beam is lost after the second station trips.

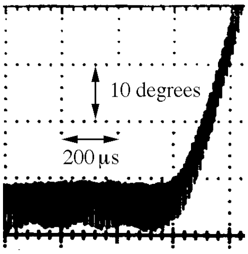

Figure 2: Change of the longitudinal phase of the beam when a crowbar circuit works for two SC stations.

The observed phase shift implies that the beam energy is transiently varied by more than 0.5 %. A large transverse orbit drift was also observed. It is considered that the beam optics is optimised at the nominal energy and the large energy deviation results in the transverse orbit drift. It is thus necessary to abort the beam before the beam energy deviation becomes large.

### 2.3 Beam Abort without BPA

Interlock signals in the RF system are connected to the beam abort system. It turned out, however, that the beam abort triggered by the interlock signals does not help all cases: one reason is that some of the interlock signals are not very fast and it takes more than 1 ms until the beam is aborted. For example, there is no fast signal output from the power supply to indicate the crowbar circuit working. Another reason is that the accelerating field in the cavity can become abnormal due to discharge, breakdown or other reasons prior to detection of any interlock signals. Consequently, the BPA is required which aborts the beam whenever the beam phase deviates from a nominal value.

## 3 BEAM PHASE ABORT

### 3.1 System Description

Fig. 3 shows a block diagram of the BPA. Beam signal detected by a pickup electrode is transmitted to a high-Q filter at the RF frequency. The output signal of the filter and the RF reference signal are down-converted to an intermediate frequency of 5 MHz and the relative phase of these signals are detected. Thus the longitudinal phase of the beam is detected with respect to the reference RF.

When the phase deviates from a nominal value, it is regarded as an abnormal phase. The DC component of the signal is blocked in order not to respond to the synchronous phase shift due to bunch current change or slow phase drift due to temperature change. After the abnormal phase is detected, it waits for 20 μs and checks if the beam intensity is above threshold level or not. If above the level, a request signal is triggered out to the beam abort kicker. The delay is introduced to distinguish the case that the abort request is really needed from the case that the beam is already lost or aborted by other reasons and the phase change is observed as a result.

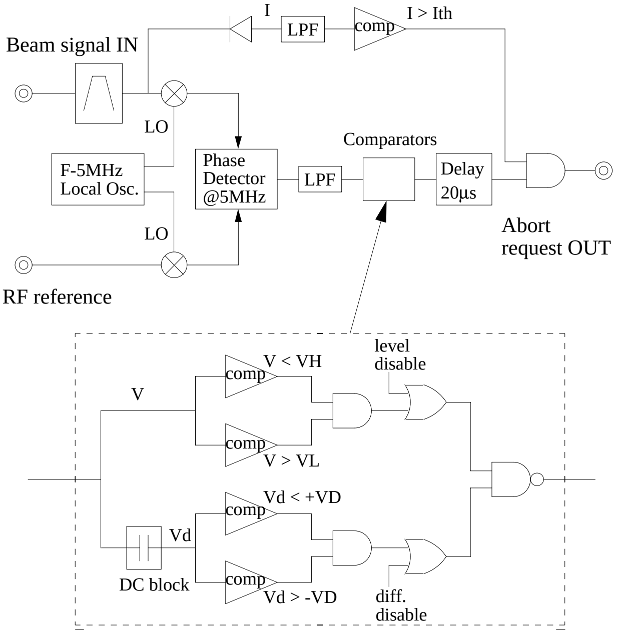

Figure 3: Block diagram of the Beam Phase Abort.

### 3.2 Unlucky Accident

The BPA was installed in HER in April 2001 and in LER in May 2001. It was observed that the beam is aborted typically within 400 μs after a trip occurs. Since then until the summer shut down the frequency of serious radiation on the Belle detector due to the trips was greatly reduced and no serious damage on the movable masks was observed. Thus the effectiveness of the BPA was demonstrated.

Nevertheless, there was an accident that a groove on a movable mask was made again in November 2001: this particular case was not saved by the BPA. The reason is understood as follows. As shown in Fig. 4, the beam phase started to shift forward, but the phase returned backward before it reaches to the threshold level. It took about 1.5 ms until the abort request signal is triggered, much longer than the usual cases. The unstable beam was lost before the abort kicker worked: the lost beam hit the mask. It is also supported by the observation of PIN diode signals.

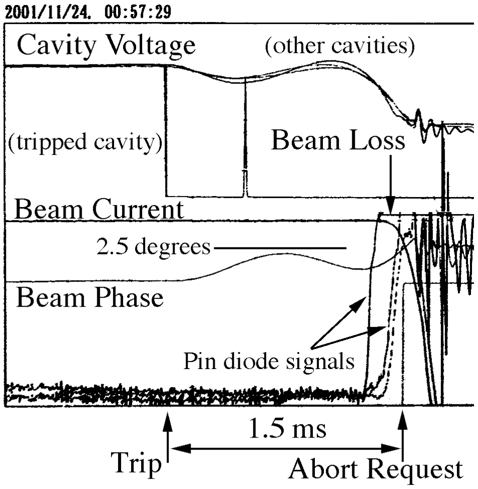

Figure 4: A movable mask was accidentally damaged in Nov. 2001. The beam phase returned before reaching to the threshold level of 2.5 degrees.

The reason for the strange behaviour of the phase in this case is considered as follows: the coupling between the cavity and the input wave-guide was obstructed due to a discharge, which resulted in abnormal high Q-value of the tripped SC cavity. The resonant frequency of the cavity and the amplitude and phase of the accelerating field became out of control. Then it happened that the field in the tripped cavity was abnormally excited.

### *3.3 Improvement on BPA*

In order to avoid such unlucky cases, measures have been taken. Firstly, the threshold phase was reduced from 2.5 degrees to 1 degree. In the previous case, the beam could have been aborted safely before the phase abnormally returned, if the threshold of 1 degree had been adopted. Secondly, the delay time in the signal transmission line of the abort system due to long cables along the ring and noise-cut-filters has been reduced from 160 µs to 80 µs.

Fig. 5 shows a typical example after the improvements were completed. When a trip occurs, the beam phase starts shifting forward. After about 150 µs, the phase deviation reaches to the threshold level of 1 degree. The time depends on the beam current or number of tripped RF stations. After the additional delay of 20 µs described in Section 3.1, the request signal is triggered out. Then the beam is aborted after the delay of 80 µs due to the cables and filters. Total delay is about 250 µs, which is sufficiently short, and the beam is aborted before it becomes unstable.

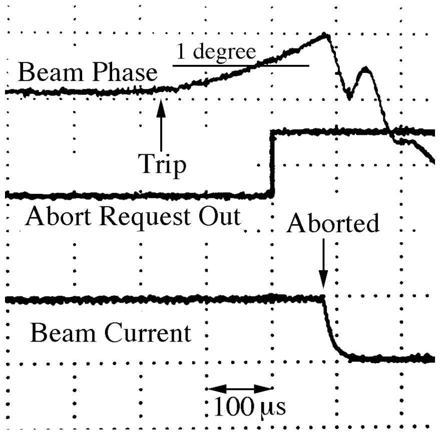

Figure 5: Typical example after the BPA was improved. The beam is aborted in about 250 µs from the trip.

### *3.4 Abort by Cavity Voltage*

In addition, Voltage of Cavity Abort (VCA) was installed in each SC station as a backup for the BPA. It generates an abort request signal when the accelerating voltage of any cavity deviates from a nominal range. Among several types of trips, some trips are characterised by fast drop of the cavity voltage, as in the case of Fig. 4. For such trips the VCA works faster than the BPA.

## 4 RESULTS

After the improvement of the BPA was completed and the VCA was installed in Jan. 2002, neither serious radiation on the Belle detector nor additional groove on the movable masks was generated by any RF trip in five months operation. It is confirmed that they effectively protect hardware components against unstable beam caused by the RF trips. Thus the troubles caused by the RF trips have been solved by the BPA together with the VCA.

Besides these protections, other efforts are in progress. One is the beam abort by signals of PIN diodes along the ring and the Belle detector [3]. The other is to change the material of mask head from copper to titanium that has higher melting temperature [4]. Up to now four masks among sixteen in HER have already been replaced with titanium head ones. It is considered that the risk will be further reduced when the change to titanium is completed in the next summer shut down.

## 5 REFERENCES

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[3] M. Arinaga et. al., "KEKB Beam Instrumentation Systems", to be published in NIM-A: KEK Preprint 2001-157.

[4] Y. Suetsugu et. al., to be published.