

RF ACCELERATING VOLTAGE OF PLS-II SUPERCONDUCTING RF SYSTEM FOR STABLE TOP-UP OPERATION WITH BEAM CURRENT OF 400 mA

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Abstract

During the beam store test up to 400 mA in the storage ring, it was observed that the vacuum pressure around the RF window of the superconducting cavity rapidly increases over the interlock level limiting the availability of the maximum beam current storing. We investigated the cause of the window vacuum pressure increment by studying the changes in the electric field distribution at the superconducting cavity and waveguide according to the beam current. An equivalent physical modeling was developed using a finite-difference time domain (FDTD) simulation and it revealed that the electric field amplitude at the RF window is exponentially increased as the beam current increases, thus this high electric field amplitude causes a RF breakdown at the RF window.

INTRODUCTION

As the RF accelerating voltage increases, the energy acceptance increases, as a result, the injection efficiency becomes higher. However, the energy acceptance of 2.5% is already sufficient for the injection efficiency of the PLS-II SR [1,2]. Therefore, the effect of the RF accelerating voltage higher than 3.6 MV on the injection efficiency is saturated. The Touschek lifetime keeps increasing until the RF accelerating voltage reaches about 3.6 MV, but it gets lower for the RF accelerating voltage higher than 3.6 MV. The longitudinal bunch length becomes shorter as the RF accelerating voltage increases as shown in Fig. 1(a). The shorter bunch can cause the problem of ion instability due to the short bunch interacting more strongly with the impedance of the vacuum chamber, enhancing outgassing in some local points. For an instance, the loss factor of the SC cavity taper section in the PLS-II SR is calculated and shown in Fig. 1(b). When the RF accelerating voltage increases from 3.6 MV to 5.0 MV, the beam bunch length is reduced by 17.5% and the loss factor is enlarged by 26.4%. This enlarged loss factor means that more power loss due to the wake-field occurs at the taper section increasing the surface temperature and vacuum pressure. . Therefore, it is recommended that the total RF accelerating voltage be kept at around 3.6 MV.

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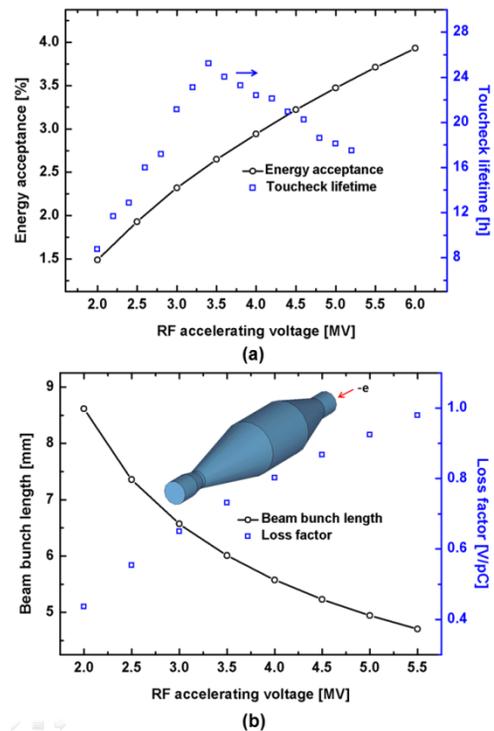
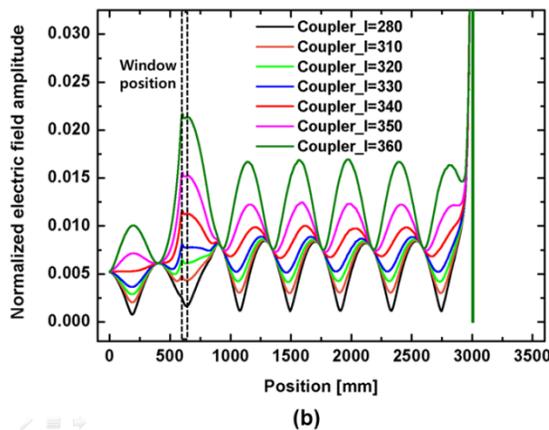
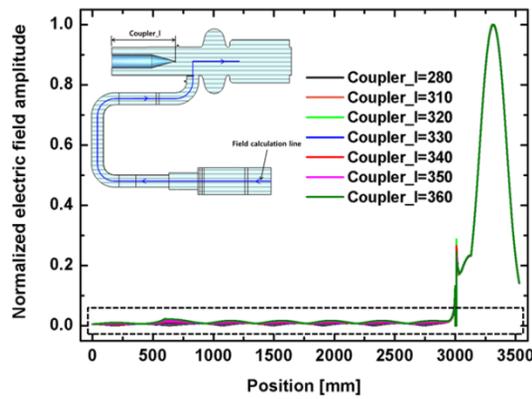


Figure 1: (a) Calculated energy acceptance and Touschek lifetime and (b) the beam bunch length and the loss factor of the PLS-II SC taper section. The three-dimensional modeling of the SC taper section is shown in the inset.

BEAM STORING MACHINE STUDY

The measured forward power, reflect power and window vacuum pressure from Fig. 2(a) are plotted to the beam current domain and shown in Fig. 2 together with the calculated beam power, forward power and reflect power of SC2 with the RF accelerating voltage of 1.2 MV. The calculated and measured powers are well matched until the beam current reaches 235 mA. However, the measured powers become unstable and show difference from calculated powers when the current is higher than 235 mA. Both the forward power and the reflect power are larger than those calculated. That means that the coupling ratio of the cavity is changed. When the beam current is dumped, it reaches 259 mA due to the window vacuum high interlock. The unpredictable changes in the coupling ratio and the rapid increment of window vacuum pressure strongly suggest that the changes in the electric field distribution must be examined at and around the ceramic window in the beam current domain.



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Figure 2: (a) Changes that occurred in the simulated normalized electric field amplitude due to Coupler₁ and (b) the magnified graph of the dotted-box region shown.

ELECTRIC FIELD DISTRIBUTION AT CERAMIC WINDOW

The electric field distribution is simulated using a full three-dimensional finite-difference time-domain (FDTD) simulation code, CST Microwave Studio [3]. To directly compare the electric field amplitude at the cavity and waveguide in the case of different Coupler₁, the field calculation line is set as drawn in the inset of Fig. 2. Then, the electric field amplitude along the line is simulated and plotted in Fig. 2(a). Here, the electric field amplitude for each Coupler₁ is normalized to the maximum value at the cavity center, because the LLRF system controls the cavity RF accelerating field to be fixed despite the changes in the beam power and beam current. The magnified view of the dotted-box region is shown in Fig. 2(b). The SC acts like a wall, so the resonance field is built up in the waveguide region. The RF window is located at the position of minimum electric field when Coupler₁ is short. That means the window is located at the anti-node of resonance field with no beam current presence. This is a common RF circuit design criterion. However, as Coupler₁ is longer, the phase of resonance

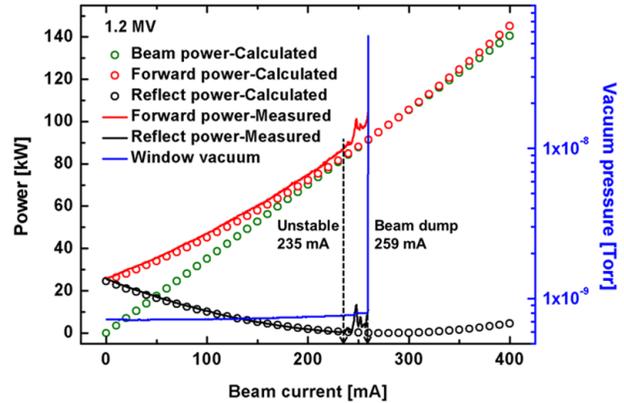


Figure 3: The beam power, forward power, and reflect power calculated, and the forward power, reflect power measured, and the window vacuum pressure of SC2 in the beam current domain during the beam store test with the RF accelerating voltage of 1.2 MV.

field is changed to invert so that the window is now located at maximum electric field amplitude. In addition, the maximum electric field amplitude of the resonance gets higher as Coupler₁ increases because the forward power should be increased to maintain the cavity RF field. That means that the electric field amplitude at the RF window gets higher as the beam current increases.

DISCUSSION ON THE ELECTRIC FIELD AMPLITUDE AT THE RF WINDOW

The RF ceramic window which allows an RF power matching between air and ultra-high vacuum parts is made of alumina with a thin Ti/N coating. The thin film suppresses the multipactor effect on RF alumina surface due to its low secondary electron emission yield^{7,8}. Nevertheless, the RF window has more chance of RF breakdown which is caused by the multipactor effect (electron multiplication on the surface) and/or the discharge of accumulated charges that occurs when the RF window is exposed to a higher electric field. As the beam current increases, the electric amplitude at the RF window exponentially grows as shown in Fig. 3(b). Even though a well-conditioned RF window withstands at higher electric field than a newly-installed RF window does, the RF breakdown with the increasing of vacuum pressure is inevitable. In addition, the standing wave ratio of the RF window can be varied in the early stage of RF breakdown due to the multipactor effect and, therefore, the forward power and reflect power becomes unstable⁹. The maximum available beam current is limited to the beam current where the unstable behavior of the forward power and reflect power occurs.

RF ACCELERATING VOLTAGE FOR 400 mA TOP-UP OPERATION

The maximum available beam current is estimated as a function of the RF accelerating voltage. Based on this estimation, we set the total RF accelerating voltage to 4.95 MV and successfully carried out the top-up operation test with the beam current of 400 mA. During the test the gap distance of IDs is set to the value of normal user service, and the total energy loss is about 1242 keV/turn (energy losses by radiation in bending magnets and IDs are 1042 keV/turn and 200 keV/turn, respectively). At first, the RF accelerating voltages of each SC are equally set to 1.6 MV as shown in the region A in Fig. 4. The SC2 RF accelerating voltage is controlled at slightly lower than the setting value because the LLRF output power limit is set to wrong value by mistake. Nevertheless, the stable top-up operation with beam current of 400 mA beam is observed. The beam current slip from 400 mA is caused by the klystron-modulator fault of the linear accelerator (LINAC) which injects 3 GeV electrons to the PLS-II SR. The vacuum pressure of the SR vacuum chamber is higher than that of normal state because it is first time to operate the SR in 400 mA top-up operation. The high vacuum pressure reduces the beam lifetime, consequently, the injection interval should be changed (from 180 to 120 seconds) to maintain 400 mA top-up operation.

However, no significant problem on the RF system is observed, even though the fluctuation of the amplitude and phase of the RF field is higher than the operation limit because of the rough setting of LLRF control parameters. The reflect power of SC2 is measured to be around 1-3 kW. In order to secure the operation margin and to reduce the chance of RF breakdown in the electric field at the RF window for a stable long time user-service operation, the RF accelerating voltages of each SC are equally set to 1.65 MV as shown in the region B in Fig. 4. At this time the LLRF power limit is set to right value and all the RF accelerating voltages are controlled at 1.65 MV. The reflection power is now increased to around 3-5 kW. The 400 mA top-up operation test was carried out for more than three hours without any fault.

CONCLUSION

We studied the effect of beam current on the electric field distribution at the SC-waveguide by simulating an equivalent physical modeling which represents beam power as an external coupling structure and waveguide port. The RF window is located at the minimum peak of the electric field distribution when no beam is presented. The phase of electric field distribution at the SC-waveguide is changed to invert as the beam current increases, and, therefore, the RF window is located at maximum peak of the electric field distribution. Moreover, the LLRF system puts more klystron forward

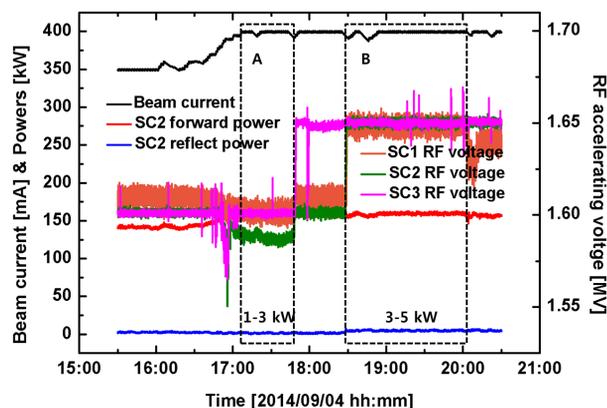


Figure 4: The beam current, RF voltages, forward power and reflect power measured during the top-up operation test with the beam current of 400 mA.

power into the SC to maintain the cavity accelerating field as the beam current increases, and, therefore, the electric field amplitude at the RF window is exponentially increased. This high electric field amplitude raises the probability of RF breakdown of the RF window, which comes with a rapid increase of the window vacuum pressure. The maximum available beam current is estimated as a function of the RF accelerating voltage. Based on this estimation, we set the total RF accelerating voltage to 4.95 MV and successfully carried out the top-up operation test with the beam current of 400 mA. Even though the Touschek lifetime is reduced to about 18 hours for the operating RF accelerating voltage of 4.95 MV, we confirmed that no significant problem occurs in the stable 400 mA top-up operation.

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