DEVELOPMENT OF BUTTON ELECTRODES FOR SUPERKEKB RINGS

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Abstract

Button-type beam position monitors for SuperKEKB rings have been designed. The RF characteristics such as beam response, trapped modes or wake functions have been simulated using 3-D E-M codes such as GdfidL and HFSS. The estimated instability threshold from the trapped modes was much higher than the radiation damping time. The prototype units have been tested in the prototype-antechambers installed in KEKB rings. The mechanical reliability and the beam responses are also reported.

INTRODUCTION

The KEKB B-Factory has been operating since 1998, keeping the world highest luminosity and accumulating integrated luminosity more than 1 ab^{-1} up to now. To investigate the flavour physics with the aid of huge integrated luminosity, improvement of the KEKB to SuperKEKB has been proposed. In SuperKEKB rings, we almost double the stored current, reduce the emittance about 1/10, squeeze betatron functions at the interaction point to achieve about 40 times larger luminosity. To reduce the beam size of the injected beam, we will construct a positron damping ring. Most of vacuum chambers around arc sections will be replaced with new antechambers to reduce the electron cloud effect in LER (4 GeV positron ring), and to overcome huge heat load from SR in HER (7 GeV electron ring). In the positron ring, the inner surface will be coated with TiN to reduce secondary emission yield (SEY) of electron clouds. The interaction region (IR) will be completely re-designed with much more complicated structure. Since all of the modifications shown above change the requirements for beam position monitors, it is necessary to evaluate and re-design the BPM electrodes.

We have designed N-type feedthroughs (FTs) with the button electrode of diameter of 12 mm for KEKB rings[1]. Those FTs were brazed to a vacuum chamber of Cu directly with good precision except several special region such as IR or a monitor test section which are made of aluminium vacuum chambers. Up to now, no major trouble was found on the FTs. However, for the SuperKEKB, the original N-type BPM will have the following difficulties:

- Since the FTs are already assembled under blazing process, the second blazing process to the vacuum chamber needs to be controlled with great care not to break the FTs with exceed temperature. We will need huge trials before establishing the final procedure.
- It is fairly difficult to repair the electrodes even if the case of the FT are fairly suspicious to such as shorted circuit or deformed output. The minimum unit of replacement is a quadrupole vacuum chamber unit; not realistic in most cases.
- Because of the large structure, a center frequency of the trapped mode (HOM) around a button-head stays rather lower frequency, around 5 GHz. The threshold beam current of the longitudinal coupled bunch instability caused by this HOM is estimated to be near the present maximum beam current of KEKB[2].

We have developed a BPM electrode with a vacuum flange-connection which will be used for most of a new vacuum chamber and the new damping ring, and an IR special electrode capable for very tight space and large beam power. The RF characteristics, beam response, wake function and beam impedance have been evaluated using 3D electromagnetic codes such as HFSS[3] and GdfidL[4]. The trial pieces of the electrodes have been installed in a vacuum chamber as a position monitor and been checked with the beam. The main parameters of SuperKEKB rings including damping ring are shown in Table 1.

Table 1. Main parameters of SuperKEKB rings (HER: electron, LER: positron, DR: positron damping ring)

	LER	HER	DR	
Energy	4.0	7.0	1.05	GeV
Circumference	3016		135	m
RF frequency		508.886		MHz
Beam current	3.8	2.6	0.08	A
Bunch number	2503		4	
Bunch length	6	5	5	mm
No. of BPM	~450	~450	84	
H emittance	3	5	13	nm rad
Coupling	0.4	0.3	10	%

NORMAL BPM ELECTRODE

Mechanical structure

A button electrode for SuperKEKB rings needs to have enough mechanical precision, at least the position error of the BPM to the level comparable to the errors coming from the gain or loss error of other components such as cables. Also the structure should be capable to the beam power much larger than KEKB. An RF connector should have full reliability on long term operation. Longitudinal coupling impedance of the BPM needs to be reduced lower enough not to cause coupled bunch instability with maximum beam current. Since the vacuum chambers of the LER and the damping ring (DR), including monitor section will be coated with TiN to reduce the SEY, it is necessary to assemble the BPM heads after the coating

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process; in the present plan, this will be made in KEK by ourselves. This require us to design the BPM heads to be connected with vacuum-sealing flange to the monitor chambers. To satisfy the requirements given above, we will have the following design principles as:

- The electrode and the FT will be assembled to the vacuum chamber with the vacuum-sealing flange with enough mechanical precision. This also gives us easy accessibility of the electrode after the assemble.
- To reduce the coupling impedance and to increase the frequency of the trapped mode higher than bunch form factor, the button size and the vacuum seal should be reduced by about the half of the present KEKB button.
- The inner conductor of the RF connector should be pin with jack structure to keep good electrical contact with long term operation.

To satisfy the requirements, we have designed the button electrode based on the SMA-type FT used for the bunch feedback system[5] and interaction region (IR) special BPM on KEKB as shown in Fig. 1. The diameter of a button head is 6 mm with thickness of 3mm. The inner conductor is supported and sealed with an alumina ceramics of ε_r=9.7. In the air side, a reverse-type SMA connector is designed to keep the good electrical contact under long term operation.

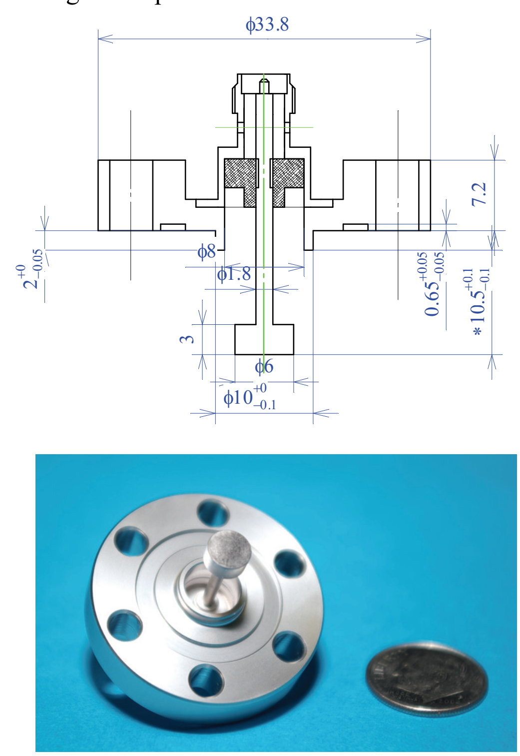

Figure 1. Drawing (top) and the photo (bottom) of a normal BPM electrode for SuperKEKB.

It has a circular flange of diameter of 34 mm made of low carbon stainless steel to connect the vacuum chamber using Helicoflex seal. The metal part for the FT including inner conductor and the button are made of Kover. It is blazed to the flange simultaneously during assemble of the FT. We have also manufactured a non-magnetic BPMs using Ti for the FT and the button for use under larger magnetic field such as very near to the quadrupole magnets. The position of the button will be fixed with the precisely defined projection of the BPM flange and the notch of the vacuum chamber within 0.1 mm. Figure 2 shows the monitor chamber in wiggler section.

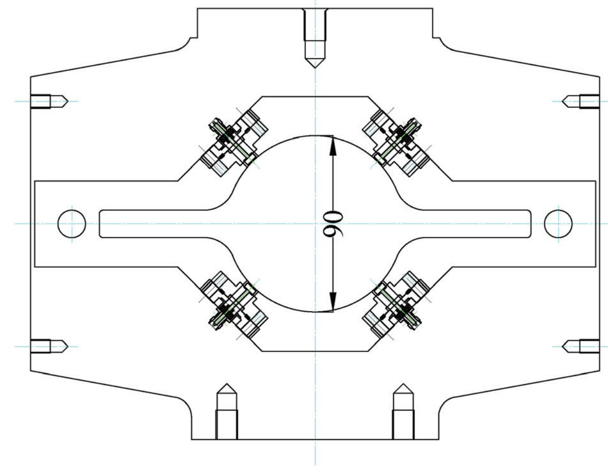

Figure 2. LER monitor chamber in wiggler section. The cut off frequency of the lowest waveguide mode is 930 MHz.

Frequency-domain simulations

We have simulated the frequency response of the button using HFSS. Both the boundary condition of the button and the RF connector were defined as impedance matched ports. Figure 3 shows the S-parameter with the comparison of N-type KEKB-LER BPM where mode 1 is the lowest coaxial mode.

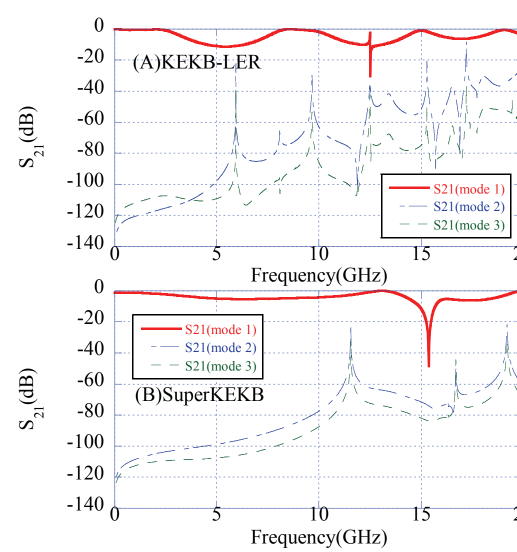

Figure 3. Simulated S-parameter of KEKB LER BPM (A) and SuperKEKB BPM (B).

With the better impedance matching around the ceramics, and with the smaller structure, S_{21} response of the SuperKEKB BPM is much smoother than the N-type BPM. The frequency of the lowest trapped mode around the button (TE-mode) increases from 6 GHz to 12.5 GHz, and the trapped mode around ceramics also increases from 12 GHz to 16 GHz. With the bunch length of 6 mm, the frequency shift reduces the coupling impedance and the risk of possible damage due to HOM.

Time-domain simulation

We have estimated the output of the BPM, longitudinal and transverse wake function and the coupling impedance using GdfidL. Figure 4 shows the cut plot of GdfidL model of 1/4 structure where the size is 111 mm, 109 mm and 50 mm in horizontal, vertical and longitudinal, respectively. With the isotropic mesh size of 0.2 mm and the bunch length of 6 mm, it needed about 5h30min to get the wake function up to 5 m using 32 cores of Opteron. Figure 5 shows the simulated output of the BPM in both time domain (A) and the frequency domain (B).

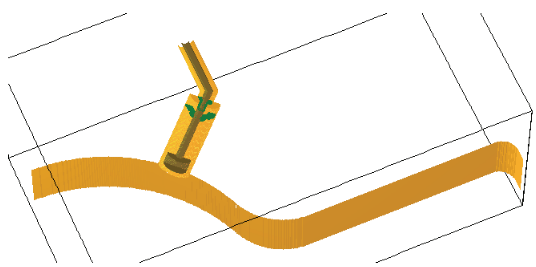

Figure 4. Cut plot of GdfidL 1/4 model of LER BPM.

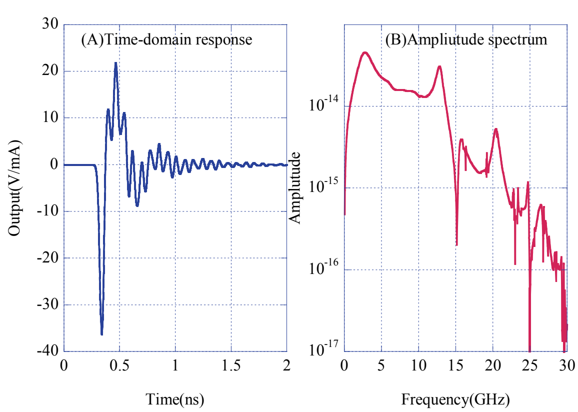

Figure 5. Simulated output of SuperKEKB LER BPM in time-domain (A) and the frequency-domain (B).

The estimated longitudinal loss factor was 0.16 mV/pC per a BPM chamber. The coupling impedance is shown in Fig. 6. By fitting the result, we obtained the Rsh~2 Ω, Q~38 and the center frequency (CF) of 14.8 GHz. The estimated growth time of the longitudinal coupled-bunch instability in the worst case is slower than 120 ms with maximum beam current; it is much longer than the radiation damping time of 37 ms. In the case of present N-type BPM, the estimated impedance by MAFIA T3 were Rsh~10 Ω, Q~48 at 7.3 GHz. The worst growth rate is around 7 ms [2] with the beam current of 3.8 A and will not be safe for use of SuperKEKB. The wake field of ultra short bunch (0.5 mm) was also calculated using windowwake mode of GdfidL to estimate the threshold current of the microwave instability. The contribution of the BPM was much smaller than other impedance sources such as vacuum components.

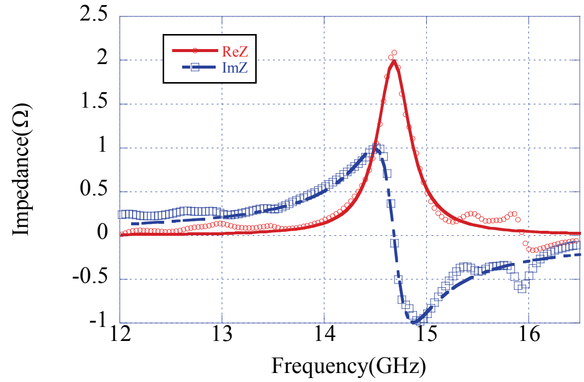

Figure 6. Estimated longitudinal coupling impedance of the SuperKEKB LER BPM.

BPM for positron damping ring (DR)

The positron damping ring (DR) will be constructed to reduce the beam size of positron beam at injection. For the position monitor, we plan to use the same BPM FT as main rings for the DR. To suppress the electron cloud effect it is planned to use an antechamber with TiN coating. Since the size of the vacuum chamber is much smaller, about 34 mm in diameter, than that of the main rings, the impedance of the BPM might affect the beam. We have made the GdfidL simulations and obtained the longitudinal coupling impedance, transverse kick factor and the wake function for ultra-short bunch beam. Figure 7 shows the 1/2 GdfidL model of DR BPM.

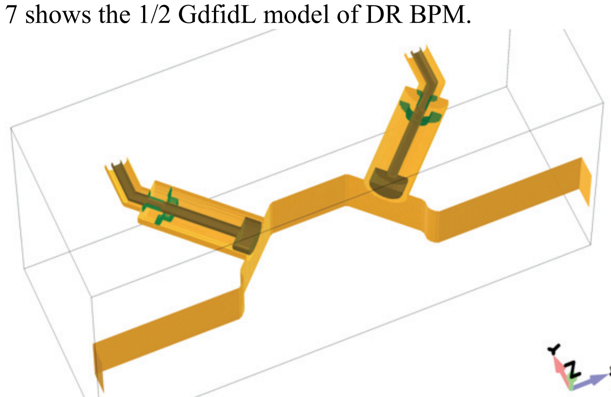

Figure 7. DR BPM 1/2 model for GdfidL.

By fitting the result, we obtained the impedance of Rsh~38 Ω, Q~104 at 14.8 GHz, and the longitudinal loss factor of 2.6 mV/pC for bunch length of 5 mm. Though the impedance itself is larger than that of SuperKEKB LER, the threshold current of the longitudinal coupled bunch instability is much larger than the maximum beam current. The transverse kick factors and wideband wake from ultra-short bunch were also calculated and confirmed to be negligibly small[6].

IR SPECIAL BUTTON ELECTRODE

Mechanical structure

Since the design beam size at interaction point (IP) of SuperKEKB is much smaller than that of KEKB, monitoring the beam position around IR and making fast position feedback is essential to keep good collision. Among the position monitors of IR, monitors between IP and the final focusing quadrupole magnets have much importance because it reflects pure beam position not affected by the error of strong magnets around IP. It is however not easy to install the position monitors there because of fairly tight space, terribly difficult accessibility and the strong magnetic field of superconducting solenoid of the Belle II detector. The inner-diameter of the vacuum chamber is 20 mm so the output power from the beam will be much larger than the normal BPM placed at the monitor chamber of diameter of about 90 mm. Figure 8 shows the designed special FT for nearest IP.

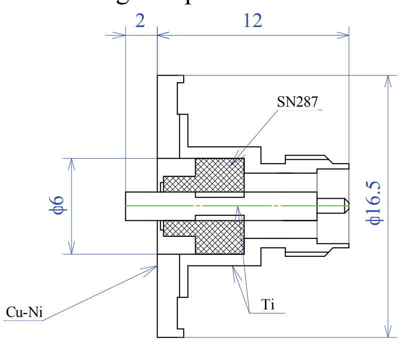

Figure 8. Drawing of a IR special feedthrough.

The button head is a simple rod of diameter of 1.8 mm to reduce the beam power. The sealing and supporting ceramics is made of silicon nitride with the dielectric constant of 7.9 that has lower dielectric loss than alumina ceramics. The body and the rod are made of titanium and blazed to the flange made of CuNi. Since the vacuum chamber will be made of Cu, the button block will be welded using electron beam as shown in Fig. 9

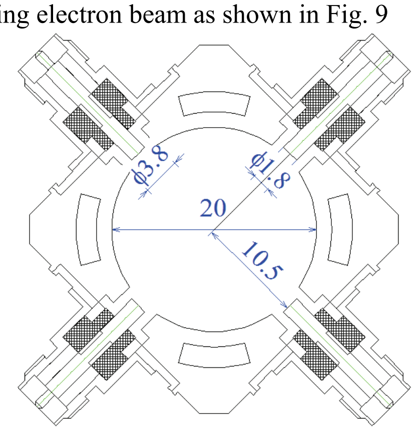

Figure 9. Nearest IP BPM.

We have manufactured several trial FTs and examined the breaking strength of the center rod to the ceramics. The results was about 120 N, much weaker than normal SMA FTs of around 1 kN. Though the strength satisfy the minimum requirement, we will try to improve the strength. Figure 10 shows the photo of the feedthrough.

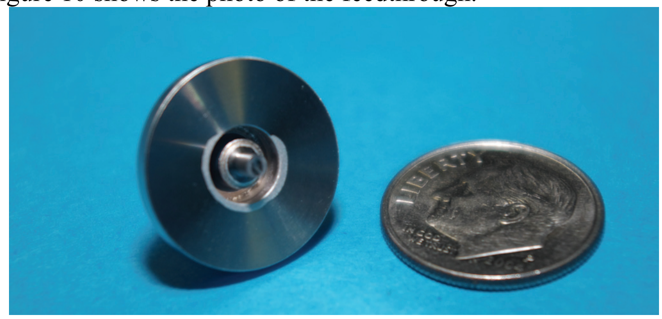

Figure 10. Photo of the nearest IP BPM FT.

3D electromagnetic simulation

The frequency response of the button was simulated using HFSS. As shown in Fig. 11, the frequency of the trapped mode both around the head and around ceramics became much higher frequency where almost no beam spectrum exist.

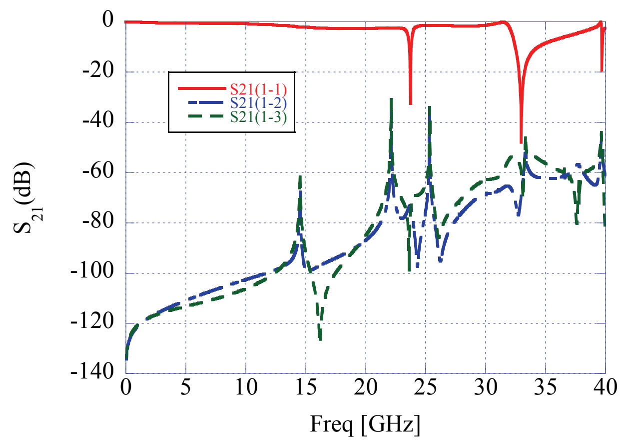

Figure 11. Frequency response of the IR special BPM.

With GdfidL, we have simulated the output of the BPM as shown in Fig. 12 where the bunch length was 5 mm and the bunch charge was 10 nC.

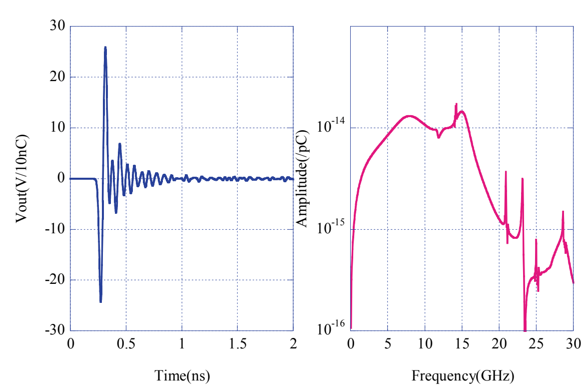

Figure 12. Simulated BPM output for IR special BPM.

The impedance was also estimated from the wake simulation of the GdfidL. The fitted result was Rsh~0.3 Ω with Q~200 at 14.3 GHz, which were negligibly small.

By summing the BPM output for the nominal bunch filling pattern, we obtain the total beam power passing through the FT, and the power level of detection frequency of 508 MHz. With the maximum beam current of 3.8 A, the estimated power level of 508 MHz will be around 6 dBm and the total beam power will be around 10 W, which is similar power at the FT near IR BPMs in KEKB where both HER and LER beam pass in the same BPM chamber with large horizontal offset.

BEAM RESPONSE WITH THE REAL KEKB BEAM

We have installed two sets of test BPM chambers with the new BPMs at Nikko straight section and south arc of KEKB-LER, then observed the raw BPM output and the beam positions. Figure 13 shows a photo of BPM chamber installed at south arc of KEKB-LER. By the gain

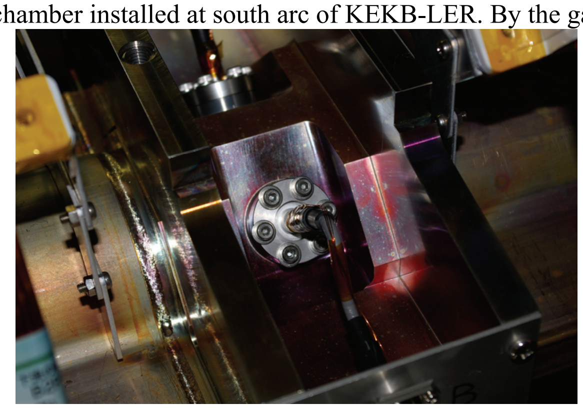

Figure 13. Test BPM chamber installed in KEKB-LER.

mapping using beam, we have found rather larger gain deviations up to 10% than those of the present BPMs. By observing the flange connection, we have found rather larger gaps (~0.2 mm) on several flanges even though no vacuum leak were found. To check the possibility that the Helicoflex gasket might be stiff enough to prevent the touch of the projection to the notch, we have made a simple test flange of ICF152 with BPM interface. With this test set, we have checked the gap changing the torque of the bolt with and without the gasket. The gap difference with and without the gasket was less than 0.01 mm when fasten with 6 Nm of torque. Therefore, we have tried to tighten the bolt much more on the real BPM and measured the gain difference again and found the resulting gain deviation has been reduced. This concludes that if we could control the torque of the bolt, we will be able to set the BPM flange to the correct position.

Figure 14 shows an example of observed raw beam signal with the bunch current of around 1 mA where bunch spacing was about 6 ns. Though it is not so easy to compare the result with the electromagnetic simulation of GdfidL due to the long cable and the insufficient bandwidth of the oscilloscope, the signal level was as expected. The beam spectrum was also observed with a spectrum analyzer and was almost in good agreement with the simulation.

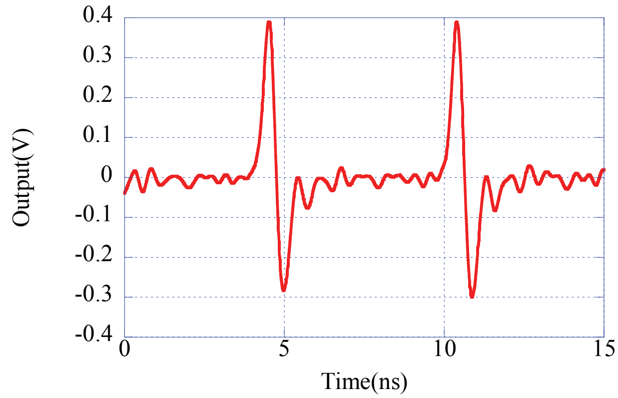

Figure 14. The raw BPM signal observed with a 1.5 GHz real-time oscilloscope. The length of a thick, low-loss cable from BPM to the oscilloscope was about 50 m.

SUMMARY

We have designed the BPM heads for SuperKEKB rings in normal section and the damping ring, and the special BPM for the IR nearest position monitor. The RF and beam coupled response such as frequency response and coupling impedance are estimated using 3D electro-magnetic simulation codes such as HFSS or GdfidL. The impedance was low enough not to cause the coupled-bunch instability. The broad band characteristics was also calculated using much shorter bunch and the broad band impedance was confirmed small enough. Simulated signal output showed enough level for detection frequency and safe level for total pass power of the feedthrough.

The prototype monitor chamber was installed in KEKB-LER and the beam response was observed. The response was as expected and no major difficulty was found up to now.

We will replace most of the BPM chamber with the new BPM unit on SuperKEKB. The new damping ring for positron beam will also use the same type of BPM.

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