R&D ON VACUUM COMPONENTS FOR HIGH-CURRENT ACCELERATORS

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Abstract

R&D on various vacuum components adaptable to future high-current accelerators has been continuously progressing at KEK. Copper beam ducts with one or two ante-chambers were designed to dilute the synchrotron radiation (SR) power density, and also to suppress photoelectrons around beams. Inner surfaces with a low secondary electron yield (SEY) were investigated to mitigate electron-cloud formation. Bellows chambers and gate valves with high thermal strength and low beam impedance were developed. A special flange with no gap at the connection point was designed. A novel movable mask (collimator) with low beam impedance was recently proposed. These components have been installed at the KEK B-factory (KEKB), and the performances have been investigated using an intense beam of up to 1.7 A.

INTRODUCTION

In future high-current accelerators, such as Super B-factories, a stored beam current of several amperes and a bunch length of a few mm are required to achieve a luminosity on the order of 1×10^{36} $cm^{-2}s^{-1}$ [1, 2]. These parameters impose very severe challenges to the vacuum system [3, 4]. The beam duct has to manage the synchrotron radiation (SR) power density up to several tens Wmm^{-2}. The vacuum components should have low beam impedance, and be able to stand up against the intense higher order modes (HOM) at the same time. Suppression of the electron cloud instability (ECI) [5] is also a serious problem in a positron ring. These are common key issues not only for a high-current factory machine, but also for the dumping ring (DR) and the collimators of the international linear collider (ILC), and the next generation of SR rings, where a very low emittance is required [6, 7].

R&D on various vacuum components to meet these demands has been progressing at KEK [8-17]. Copper beam ducts with antechambers were designed and manufactured [8, 9]. The antechamber scheme was adopted to deal with the intense SR power and to suppress photoelectrons at the same time. The effects of the inner coatings of NEG materials (Ti, Zr, V) and TiN were studied, which were said to have low secondary electron yields (SEY) [10, 11]. Bellows chambers and gate valves with a comb-type RF-shield were newly developed [12-14]. A special connection flange was designed and examined, which has a small step, or gap, inside, even for a beam duct with antechambers [15]. A movable mask (collimator) with low impedance was recently proposed and the study has just begun [16].

These components have been installed for testing at the KEK B-factory (KEKB) [18, 19]. KEKB is an electron-positron collider with asymmetric energies, and consists of two rings, that is, a 3.5 GeV positron ring (Low Energy Ring, LER) and an 8.0 GeV electron ring (High Energy Ring, HER). The maximum stored beam currents of LER and HER are 1.7 A and 1.4 A at 1389 bunches, respectively. At present, KEKB is the most suitable machine for R&D about future accelerators with high intensities. The R&D is progressing based on various experiences in the vacuum system of KEKB [20, 21]. The concepts of these newly-developed vacuum components and the results of recent studies are reviewed here.

BEAM DUCT

The R&D of vacuum components began with a beam duct with an ante-chamber in 2003 [8, 9]. The beam duct consists of two channels, i.e. a beam channel where a beam circulates, and an SR channel (ante-chamber) aside where synchrotron radiation (SR) passes through. By using the ante-chamber scheme, the maximum power density of SR can be diluted at the side wall. Photoelectrons inside the beam channel, furthermore, are small compared to that of a simple circular duct, which is a big merit for a positron ring to suppress the ECI.

Several kinds of copper beam ducts with ante-chambers have been manufactured, and installed into the KEKB LER. Copper (Oxygen Free Copper, OFC) was adopted for its high thermal strength and good radiation shielding property [20, 21]. The electron beam was used to weld copper to copper. The inner diameter of the beam channel was 94 mm, and the thickness was 6 mm. The depth and the height of the ante-chamber were 65 mm and 15 mm, respectively. The ducts were manufactured using two methods, that is, pressing and forming (cold drawing). A copper beam duct with two ante-chambers is presented in Fig. 1, for example. Two NEG-pump channels were placed at the top and bottom of the ante-chambers.

Beam ducts with one ante-chamber were installed in an arc section of LER. The SR power and the photon density was 3 kW m^{-1} and 8.5×10^{18} photons s^{-1} m^{-1}, respectively, at a beam current of 1 A. The critical energy of SR was 5.8 keV. Beam ducts with two ante-chambers, on the other hand, were installed at a wiggler section, where the SR hits the duct at both sides. The maximum power density and the direct photon density were about 227 Wm^{-1} and 7.5×10^{17} photons m^{-1} s^{-1} at a beam current of 1 A, respectively.

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Fig. 1 Copper beam duct with two ante-chambers for tests.

The temperatures and vacuum pressures around the ducts were monitored during beam operation up to a beam current of 1.7 A (1389 bunches). Although arcing was observed at a welding part of one model at the beginning of commissioning [8], no problem was found in other models. The temperature of the duct was slightly higher, but almost in agreement with the expectation.

From the view point of ECI, the number of electrons around the beam was measured by an electron monitor [22]. A reduction in the number of photoelectrons by one or two orders of magnitude compared to a simple circular duct was confirmed at a low-current region, less than 0.1 A, where the photoelectrons were dominant [9]. The electron number at a high-current region, such as 1.5 A, was also smaller, but the reduction was only by a factor of 4. This was because the main component of the electron cloud at the region was the secondary electrons, which were generated in a multiplication process by highly charged bunches.

COATING WITH LOW SEY

As described above, secondary electrons play a large part in the formation of an electron cloud at a high-current region. One promising way to suppress the ECI, therefore, is to apply a surface with a low SEY to the inner surface of a beam duct.

The secondary electron and photoelectron yields (SEY and PEY) of the NEG coating and the TiN coating have been studied using KEKB LER [10, 11]. These coatings are said to have a low SEY compared to metals, and the coating processes are well established. Test chambers with the NEG and the TiN coating were first installed at an arc section of the KEKB positron ring. The test chambers have a circular cross section (ϕ94 mm). The thicknesses are about a few micro-metres. The number of electrons around positron bunches was measured up to a beam current of about 1.7 A, and compared with each other.

The electron number of the TiN-coated chamber was clearly smaller than that of the non-coated copper chamber by a factor of 2. The electron number in the case of the NEG-coated chamber, on the other hand, was almost the same as that of the copper chamber. Only a small difference was observed at a high current region, around 1. 5 A.

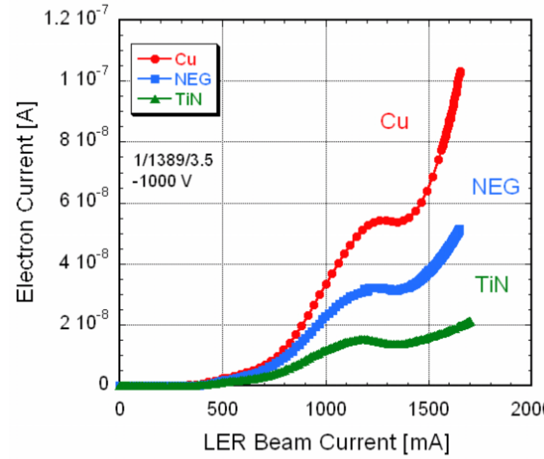

Fig. 2 Measured electron current for copper (Cu), NEG coating (NEG) and TiN coating (TiN) as a function of beam current.

Using a simulation, the maximum SEY (δ_{max}) and the PEY (η_e) of the TiN coating, the NEG coating and the copper were estimated based on the measured electron current. It was found that the TiN coating had an SEY (δ_{max} ~ 0.9) as low as that of the NEG coating (δ_{max} ~ 1.0), but the electron current was clearly smaller than that of the NEG coating, due to its lower η_e (~ 0.14). This study indicated that suppression of photoelectrons is required to make effective use of a surface with a low SEY.

To see the effect of SEY more clearly, similar studies were performed at a straight section of LER, where the direct photon number is less than 1/10 of that at an arc section. The electron number around the beam for the NEG-coated, the TiN-coated and non-coated copper chamber were again measured. The electron numbers for the TiN coating and the NEG coating were about 1/3 and 2/3 of that in the case of the copper chamber, as shown in Fig.2. The difference between the NEG coating and the copper was clear in this case. Assuming almost the same η_e for three cases, the δ_{max} values were again estimated using the previous simulation. Although the study is still in progress, the results are almost consistent with those obtained at the arc section.

BELLOWS CHAMBER AND GATE VALVES

Bellows chambers and gate valves with an RF-shield structure are indispensable to connect beam ducts with one another. The cross section has to fit to that of the beam ducts. The RF-shield should have a uniform inner surface to avoid exciting HOM, reliable electric contact to smoothly flow the beam-induced wall current, and also a high thermal strength.

Bellows chambers and gate valves with a comb-type RF-shield have been developed at KEK [12-14]. A schematic structure of a comb-type RF-shield is shown in

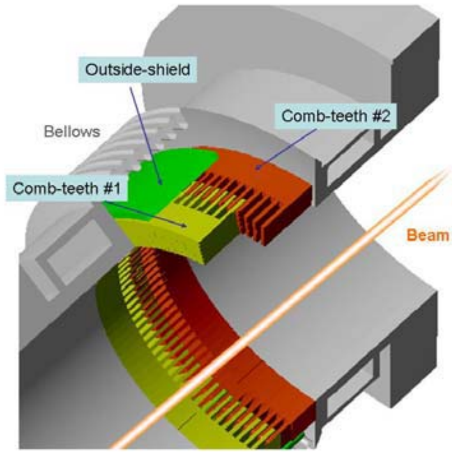

Fig. 3 Conceptual structure of a comb-type RF-shield for a bellows chamber.

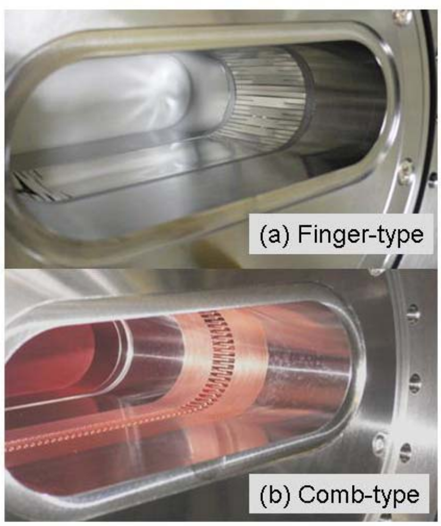

Fig. 4 Inside view of gate valves with (a) finger-type and (b) comb-type RF-shields.

Fig. 3, and an inside view of a gate valve is presented in Fig. 4, for example. The comb-type RF-shield consists of no more than thin fingers, but nested comb teeth. The TE-mode like HOM can hardly go through it. The RF-shield has a lower beam impedance than the conventional finger-type one according to a calculation. The transverse off-set, however, was limited compared to the finger-type.

The first test model of the bellows chamber with this RF-shield was installed in the KEKB LER in 2003. The inner diameter was 94 mm, and the length was 160 mm. The thickness, length and radial thickness of a tooth were 1 mm, 10 mm and 10 mm, respectively. The comb teeth were made of copper.

The temperature of the corrugation of the bellows chamber, which was located just near to the movable mask, decreased to about 1/6 compared to the case of a finger-type RF-shield, from 48°C (ΔT = 23°C) to 29°C (ΔT = 4°C) at a beam current of 1.7 A, for example. No problems, such as discharging, have been observed. The RF-shield was then adopted to bellows chambers with a race-track cross section (150 mm × 50 mm), which were installed in the KEKB HER. A reduction of the temperature by a factor of 3 was again obtained during beam operation.

A simplification of the structure has was tried in parallel. In addition to the comb teeth, the original structure (Ver.0) had small fingers at the back side between overlapped comb-teeth (Back-shield), and a spring-type shield on the outside (Outside-shield), in order to make sure of the shielding for the low-frequency components. A modified model (Ver.2), where the back-shield was omitted from Ver.0, greatly simplified the structure, and has shown no problem up to now.

Bellows chambers with the same cross section to the beam duct with ante-chambers were recently developed, as shown in Fig. 5. A comb-type RF-shield (Ver.2) was adopted for that, since it could smoothly fit to the complicated cross section. The comb-teeth and the cooling channel were OFC. The nominal length of the bellows chamber was 200 mm, and the stroke was ±4 mm.

They were installed in 2004 and revealed no problem up to now. The temperature of the bellows was about 31°C (ΔT = 6°C) at 1.7 A, which was almost the same as that of adjacent circular bellows chambers with a finger-type RF-shield.

R&D to apply the comb-type RF-shield to gate valves has been tried under collaboration with VAT Vakuumventile AG [23]. A big problem in the RF-shield for gate valves was the generation of dust due to abrasion during an open/close motion. The model Ver.2 was thus applied to the gate valves, where bending fingers were used as Outside-shield. The base design of the valve, such as the vacuum sealing mechanism, was the same as the standard one, and only the RF-shield part was modified. The tooth was pure copper, and other parts were stainless-steel (SS304).

The first test model had a diameter of 94 mm and a width of 95 mm, and was installed into the KEKB LER. The temperature at the body decreased from 45 - 37°C (ΔT = 20 - 12°C) to 28°C (ΔT = 3°C) at a beam current of 1.7 A. The decrease of the temperature rise at the body meant a decrease of HOM intruding into the inside. No problem was found in both the temperature and the

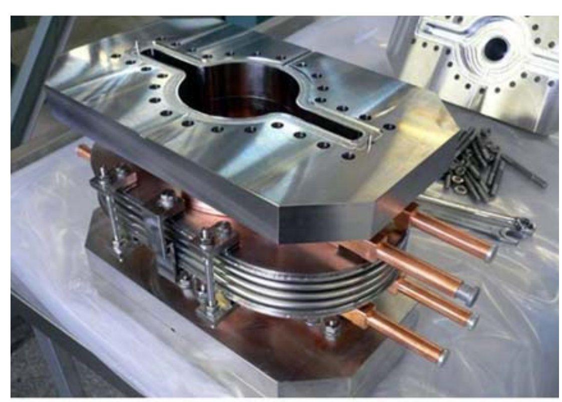

Fig. 5 Bellows chamber for beam ducts with two ante-chambers.

vacuum pressures up to a beam current of 1.8 A. The comb-type RF-shield may be suitable to the gate valve, rather than the bellows chambers, because only expansion and contraction are required, in principle, there.

As a next step, a gate valve with a race-track shape was manufactured and installed into the KEKB HER. The race-track had a width of 150 mm and a height of 50 mm (see Fig. 4). The temperature decreased form 33°C (ΔT = 8°C) to 28°C (ΔT = 3°C) at 1.35 A (1389 bunch). It was interesting that the temperature of a bellows chamber connected to the gate valve also decreased after exchanging the gate valve. This is an indication that the excited HOM decreased upon using the comb-type RF-shield.

CONNECTION FLANGE

Even connection flanges of beam ducts can be a big HOM source, since the number is huge, about 2000 per one ring. Helicoflex sealing is no longer sufficient, although the depth of a gap is about 2 mm [20]. The Helicoflex sealing, furthermore, cannot follow the complicated aperture, such as that of a beam duct with antechambers. The conventional RF-bridge is made of thin metal fingers or metal O-rings [24]. The small fingers may be able to follow the complicated aperture, but a uniform electric contact can hardly be guaranteed.

The MO-type (Matsumoto-Ohtsuka-type) flange used for a connection flange can seal a vacuum at only the inner surface using a copper gasket [15]. The copper gasket also works as a secure RF-bridge, which has no gap or step at the inner surface. The thermal strength of the copper gasket is much higher than that of thin metal fingers or O-rings.

The specially designed MO-type flange was used for the bellows chambers and the beam ducts with antechambers, as also presented in Fig. 1 and Fig. 5. It has a width, a height and a thickness of 320 mm, 190 mm and 30 mm, respectively. The material was stainless-steel 316. A vacuum seal was achieved with a fastening torque of about 16 Nm, which was almost the same as in the case of a standard circular conflate flange with a similar diameter. Baking several times up to 200°C showed no vacuum leak.

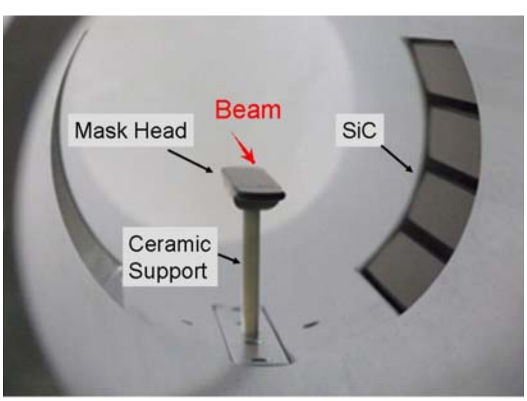

Fig. 6 Inside view of a new-type movable mask (a trial model).

No problem was found up to a beam current of 1.7 A. The temperature of flanges was about 40°C (ΔT = 15°C) at a beam current of 1.7 A. The temperature was almost the same as that of the adjacent standard circular flanges with a metal O-ring.

MOVABLE MASK (COLLIMATOR)

A movable mask (collimator) is a special vacuum component used to cut off spent particles around a nominal beam orbit, and then to decrease the background noise of the particle detector [25, 26]. The movable mask is a key component for high-luminosity machines.

The movable mask has a head (a block of metal with several radiation lengths) just near to the beam orbit. The movable mask, therefore, inherently has a high beam impedance [27]. The loss factors are typically near to 1×10^{12} VC^{-1} at a bunch length of 3 mm. Then, the parasitic loss reaches up to 200 kW, assuming a beam current of 10 A (5000 bunches).

Another problem of the movable mask is damage to the mask head due to direct hitting of the beam, where copper or titanium have usually been used [28]. The beam deposits energy in a narrow area of the head, which can melt it.

Recently, a new structure of a movable mask with low beam impedance was proposed [16]. The mask head is supported by a ceramics rod with a thin and low conductive layer at one side, which can reduce the interference between the mask head and the beam. The mask head is a copper-coated ceramics, which has a higher thermal strength compared to the metals used so far. A HOM absorber (SiC, Silicon Carbide) is prepared just near to the mask head to absorb extra HOM. An inside view of the new structure is presented in Fig. 6.

The RF-properties of the new-type movable mask was examined by simulation codes, such as the MAFIA and the Microwave Studio. The resonant frequencies, the *Q*-factors, the impedances of the trapped modes, and the loss factors were calculated. The growth rates of the coupled bunch instability under the parameters of the KEKB and the Super KEKB were evaluated, and the availability was confirmed. A test model was then manufactured and installed into the KEKB LER this winter. The performance as a movable mask will be tested, as well as the temperatures of the test model and the head, itself, during beam operation this year.

FUTURE PLAN

Following the basic R&D, as described above, a plan to replace the present circular beam ducts at a wiggler section of the KEKB positron ring by beam ducts with ante-chambers is progressing. The wiggler section has a length of about 130 m. The region includes 25 straight ducts (about 3.5 m), 13 Q-duct (ducts for quadrupole magnets, about 1.7 m) with BPM (Beam Position Monitors) and 37 bellows chambers (200 mm). The specification for the beam ducts and the BPM should be matched to those for Super KEKB. The inner surface of the beam duct will be coated by TiN to reduce the SEY. The replacement can be a final test for an upgrade of KEKB in the future.

The new movable mask will be applied to HER following a beam test at LER. The concept of the "stealth" movable mask can be applied to the clearing electrode for ECI. R&D about the clearing electrode will also begin soon.

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