

# DEVELOPMENT OF A MOVABLE COLLIMATOR WITH LOW BEAM IMPEDANCE

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## Abstract

A movable collimator (mask) with low beam impedance is proposed for high-intensity colliders. The collimator head is supported by a dielectric rod, instead of a conventional metal block or rod. Owing to the dielectric support, the beams hardly see the head, and thus the beam impedance decreases. Based on the simulation study, the first test model was manufactured and installed in the KEK B-factory (KEKB) positron ring, and tested with the beams. The head and the support were made of alumina ceramic, and the head is coated by copper. However, excess heating of the head and the support was observed from an extremely lower beam current than expected. High frequency HOM seemed to cause the considerable dielectric loss not only inside the support but also the head, which formed an RF cavity due to the copper coating. The revised model is now under design based on the experience.

## INTRODUCTION

A movable collimator (mask) is a special vacuum component equipped in colliders in order to cut off spent particles around a nominal beam orbit, and then to decrease the background of the particle detector [1–3]. The movable collimator is a key component for high-luminosity colliders. The collimator has a head (a block of a material with a sufficient radiation length) just near to the beam orbit. Therefore, the movable collimator inherently has high beam impedance [2]. The loss factor of a typical existing collimator is approximately  $1 \times 10^{12}$  V C<sup>-1</sup> at a bunch length of 3 mm. The parasitic loss, therefore, reaches up to 200 kW for a beam current of 10A with 5000 bunches, for example. Another problem of the conventional collimator is damage to the head due to the direct striking of intense beams [4].

Recently, a new structure of a movable collimator with low beam impedance was proposed [5]. The head is graphite, which has a higher thermal strength than other

metals. The head is supported by a dielectric (ceramics) rod, which can reduce the interference between the head and the beam. The support has a thin conductive layer to avoid the unnecessary charge up of the head. A HOM (Higher Order Modes) absorber (SiC, for example) can be prepared just near to the head to absorb extra HOM. The RF-properties, such as the resonant frequencies, the  $Q$ -factors, the impedances of the trapped modes, and the loss factors, were examined through simulations. The loss factor was found to reduce to approximately 1/4, compared to that of the existing one, for example.

## FIRST TEST MODEL

The first test model was manufactured based on the simulation study [5]. The inside view is presented in Fig. 1. The structure of the first model was simplified from the original design, considering easy manufacturing, and also first focusing on the proof of principle using a relatively low beam current. The head was alumina ceramics (99% Al<sub>2</sub>O<sub>3</sub>,  $\epsilon_r = 10$ ) with Cu coating ( $\sim 10$   $\mu$ m), instead of graphite in the original design. The head was a rectangular solid with sizes of 6 mm  $\times$  4 mm  $\times$  90 mm. The length was almost the same as the radiation length of Al<sub>2</sub>O<sub>3</sub>. The support was also Al<sub>2</sub>O<sub>3</sub> ceramic. The loss factor for the case of Al<sub>2</sub>O<sub>3</sub> support was higher than that of the BN support ( $\epsilon_r = 4$ ) by a factor of 2–3, but still lower than that of the existing structure. The support was also a rectangular solid with sizes of 6 mm  $\times$  4 mm  $\times$  33 mm. The head and the support consisted of one Al<sub>2</sub>O<sub>3</sub> block, which made the assembly easy. The head was not fully coated by copper due to the connection to the support, which could be a cause of a heating as described later. A thin Ti coating ( $\leq 1$   $\mu$ m) was applied at one side of the support. The resistivity of the Ti coating was 2.4 k $\Omega$  in DC. The SiC bars (15 mm  $\times$  10 mm  $\times$  90 mm) were located at the side surface of the chamber. The input power into the head should be mainly transferred by the radiation, and partially by the conductivity of the support.

## BEAM TEST

One vertical-type collimator was installed into the KEKB positron ring (LER) this winter, by replacing an existing one. The temperature of the head was remotely monitored by a radiation thermometer, which measures the radiation power at a wavelength of 1.6  $\mu$ m through a sapphire window. The temperature of bellows chambers near to the collimator and the body of the test model were also observed during the beam operation, which can be an indication of the intensity of excited HOM power. The vacuum pressure just near to the collimator was also monitored all the times.

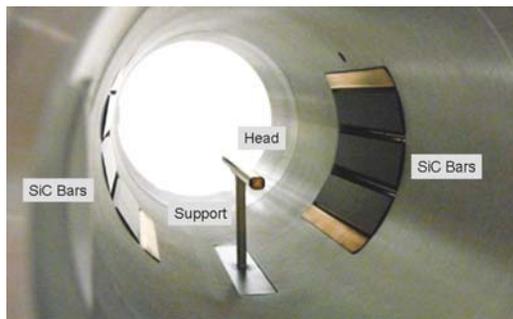


Figure 1: Inside view of the first test model of a new movable collimator.

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First of all, the performance of the collimator head was checked by controlling the position of the head at a beam current ( $I_b$ ) of 70 mA (1389 bunches). It was observed that the beam life time decreased as approaching the head to the beam orbit.

### Excess Heating

At a beam current of approximately 40 mA (51 bunches), the heating of head larger than our expectation was recognized. The measured temperature of the head was approximately 1000 K, where the emissivity ( $\varepsilon$ ) of 0.2 was set to the thermometer. The expected input power from the trapped modes and the Joule loss was about 0.11 W, and the expected temperature was approximately 320 K at  $\varepsilon = 0.02$  (shining copper). After several days of operation, however, the temperature reduced to about 70–80% at the same conditions. That indicated the change of the surface property of the head, such as the evaporation of Cu coating, or the structure of that. After that, the temperature had been almost stable. The temperature ( $T$ ) varied almost in proportion to  $I_b^2/N_b$ , where  $N_b$  denotes the bunch number, independently of the bunch fill patterns. This meant that the main input power into the head was HOM.

At  $I_b = 700$  mA (1389 bunches), however, a big pressure burst over  $1 \times 10^{-4}$  Pa was observed at the collimator, and the further temperature rise (over 1600 K) was observed at the same time. At this stage, the head was inspected by breaking vacuum, and it was found that the Cu coating had almost lost from the head. Furthermore, the connection part of the support to the head was partially melted.

These observation meant that the temperature of head had increased over 800 K (vapour pressure of copper at a vacuum pressure of  $1 \times 10^{-6}$  Pa) at 40 mA (51 bunches,  $I_b^2/N_b = 35$  mA<sup>2</sup>). Furthermore, the temperature around the connection part of the head increased near to the melting point of  $\text{Al}_2\text{O}_3$ , that is around 2600 K at  $I_b = 700$  mA (1389 bunches,  $I_b^2/N_b = 350$  mA<sup>2</sup>).

### Analysis of Excess Heating

Main causes of the excess heating should be:

- Structure of head; the  $\text{Al}_2\text{O}_3$  head with Cu coating shaped an RF cavity. The connection part of the support became a window of the cavity.
- Increase of  $\tan\delta$  (dielectric loss tangent); the increase of  $\tan\delta$  at high temperature and also high frequencies was underestimated in the original design.
- Overestimated heat transfer by radiation.

In order to quantitatively investigate the observed heating phenomena, the electromagnetic fields inside the head and the support were calculated by MAFIA 4.0, and then the temperature was estimated by ANSYS 8.0 by using the obtained field intensities taking into account of the temperature dependence of  $\tan\delta$  [6]. The calculation of electromagnetic field showed that resonance modes actually existed inside the head with Cu coating. The frequencies ( $f$ ) were in the range of 10–20 GHz. The

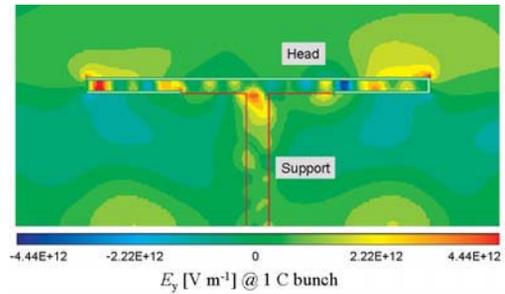


Figure 2: Vertical ( $y$ ) component of electric field inside the head ( $\text{Al}_2\text{O}_3 + \text{Cu}$  coating) and the support ( $\text{Al}_2\text{O}_3$ ) for the first test model.

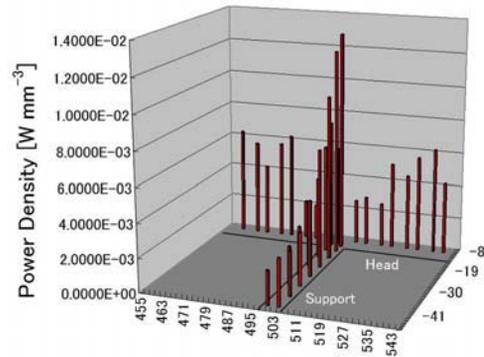


Figure 3: Power loss density inside the head ( $\text{Al}_2\text{O}_3 + \text{Cu}$  coating) and the support ( $\text{Al}_2\text{O}_3$ ) for the case of  $\tan\delta = 0.04$ .

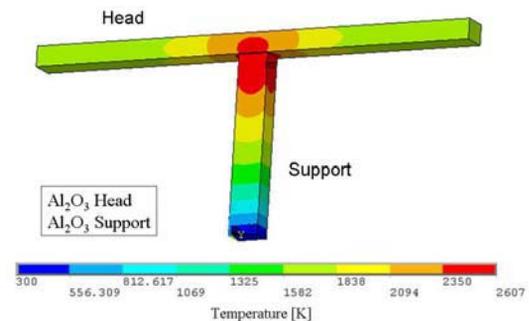


Figure 4: Temperature of the head ( $\text{Al}_2\text{O}_3$ ) and the support ( $\text{Al}_2\text{O}_3$ ), after evaporation of Cu coating.

intensity of vertical ( $y$ ) component of the electric field inside the head and the support is presented in Fig. 2. The dielectric loss density,  $P_1$ , was calculated by  $P_1 = 1/2 \omega \varepsilon_r \tan\delta E^2$ , where  $\omega = 2\pi f$ ,  $\varepsilon_r$  is the real part of the relative dielectric constant, and  $E$  is the electric field. The electric field was recorded up to approximately 30 ns, and then the frequency components were calculated by FFT. The dielectric loss was evaluated up to a frequency of 40 GHz. Here the  $\tan\delta$  was assumed to have an exponential dependence on the temperature,  $T$ , according to  $\log_{10}(\tan\delta) = 5.22 \times 10^{-4} \times T [\text{K}] - 2.27$ ;  $\tan\delta \sim 0.008$  and  $\sim 0.06$  at 300 K and 2000 K, respectively, for example.

For the case of the first test model ( $\text{Al}_2\text{O}_3 + \text{Cu}$  coating head and  $\text{Al}_2\text{O}_3$  support), the power density inside the head and the support was calculated as shown in Fig. 3,

Table 1 Calculated temperatures and loss factors for various combinations of head and support.

Type	Head material	Support material	Support			Max. T [K]		Loss Factor [V C <sup>-1</sup> ]
			$\lambda$ [Wm <sup>-1</sup> K <sup>-1</sup> ]	$\varepsilon_r$	$\varepsilon$	$I^2/N_b = 353 \text{ mA}^2$	$I^2/N_b = 2000 \text{ mA}^2$	
1 <sup>1)</sup>	Al <sub>2</sub> O <sub>3</sub> +Cu <sup>5)</sup>	Al <sub>2</sub> O <sub>3</sub>	0.01	10	0.5	(980 @35 mA <sup>2</sup> )	–	1.4×10 <sup>11</sup>
2 <sup>2)</sup>	Al <sub>2</sub> O <sub>3</sub>	Al <sub>2</sub> O <sub>3</sub>	0.01	10	0.5	2600	–	3.7×10 <sup>11</sup>
3 <sup>3)</sup>	Graphite <sup>6)</sup>	Al <sub>2</sub> O <sub>3</sub>	0.01	10	0.5	800	–	7.9×10 <sup>10</sup>
4 <sup>3)</sup>	Graphite <sup>6)</sup>	Quartz (SiO <sub>2</sub> )	0.0015	4	0.5	700	> 2000	2.7×10 <sup>10</sup>
5 <sup>3)</sup>	Graphite <sup>6)</sup>	AlN	0.1	9	0.5	480	1200	7.9×10 <sup>10</sup>
6 <sup>3)</sup>	Graphite <sup>6)</sup>	BN	0.02	4	0.5	580	1100	2.7×10 <sup>10</sup>
7 <sup>4)</sup>	Graphite <sup>6)</sup>	Diamond (C)	0.5	6	0.4	410	730	2.1×10 <sup>10</sup>

1) First mode. 2) After evaporation of Cu coating. 3) Support sizes =  $\phi 4 \text{ mm} \times 33 \text{ mm}$ . 4) Support sizes =  $1.2 \text{ mm} \times 5 \text{ mm} \times 33 \text{ mm}$ . 5)  $\varepsilon = 0.02$  for Cu. 6) Electric conductivity =  $1 \times 10^5 \Omega^{-1} \text{ m}^{-1}$ , and  $\varepsilon = 0.7$ .

for the case of  $\tan \delta = 0.04$ , for example. The estimated temperature at the head was 880 K at  $I_b = 42 \text{ mA}$  (51 bunches) with  $\tan \delta = 0.016$ ,  $\varepsilon(\text{Cu}) = 0.02$  and  $\varepsilon(\text{Al}_2\text{O}_3) = 0.5$ . That temperature is sufficient to evaporate the Cu coating, as described above. The power density inside the head was approximately  $0.002 \text{ W mm}^{-3}$ . The total input power of the head was then about 4.3 W, which is much higher than that expected from only the trapped mode and the joule loss.

If the Cu coating has gone, the structure becomes quite different. The loss factor increases by a factor of 4, and almost the same as that of the existing collimator. The temperature of the bellows chambers near to the test model was actually almost the same to the case of the old type. The calculated dielectric loss was highest at the connection part of the head. The power density there was about  $1.2 \text{ W mm}^{-3}$ , and the estimated temperature was 2600 K at  $I_b = 700 \text{ mA}$  (1389 bunches) with  $\tan \delta = 0.12$ . The temperature is almost the same as the melting point of Al<sub>2</sub>O<sub>3</sub>, as shown in Fig. 4.

The observed heating phenomena were able to be reproduced by the simulation using reasonable parameters as described above. It was also pointed out that the inadequate heat transfer, by radiation in this case, should be dangerous since the dielectric loss exponentially increases with temperature. Thermo runaway phenomenon could be occur in any cases.

## NEXT MODEL

The next test models are now under design based on the experience of the first one. The head returns to the graphite as the original design (electric conductivity  $\sigma = 1 \times 10^5 \Omega^{-1} \text{ m}^{-1}$ ,  $\varepsilon = 0.7$ ). The candidates of the support are Al<sub>2</sub>O<sub>3</sub>, BN, AlN, quartz (SiO<sub>2</sub>), and diamond (C). The BN ceramic and the quartz have a low  $\varepsilon_r$  around 4, and then the loss factor can be small. The electromagnetic field inside of the support is also weak. The AlN ceramic has similar  $\varepsilon_r$  of around 9 to the Al<sub>2</sub>O<sub>3</sub> ceramic, but has a high thermal conductivity ( $\lambda$ ), comparable to aluminium ( $\lambda = 0.17 \text{ W mm}^{-1} \text{ K}^{-1}$  at room temperature). Diamond has an  $\varepsilon_r$  of about 6, and of special note is that the  $\lambda$  ( $> 1 \text{ W mm}^{-1} \text{ K}^{-1}$ ) is higher than that of copper.

For each combination, the electric field and then the temperature of the support and head were calculated with a similar way described above, assuming the same temperature dependence of  $\tan \delta$ . The  $\lambda$  values were set to be about a half of those at room temperature here. The maximum temperatures of the support at 700 mA (1389 bunches,  $I_b^2/N_b = 350 \text{ mA}^2$ ) and at  $\sim 1700 \text{ mA}$  (1389 bunches,  $I_b^2/N_b = 2000 \text{ mA}^2$ ) are summarized in Table 1, together with the loss factors and the parameters used in the calculation. The operation at  $I_b = 1700 \text{ mA}$  (1389 bunches) is the typical one at the present KEKB. The most promising combination is that of a graphite head and a diamond support. The high  $\lambda$  value of the diamond stabilized the thermal behavior. The manufacturing of a trial model with this combination has just started. A simple combination of graphite and diamond, however, will be unusable for the super B ( $I_b \sim 10$ ,  $N_b \sim 5000$ , and  $I_b^2/N_b = 20000 \text{ mA}^2$ ), and further studies should be required.

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